Measurement of the $B_s^0 - \overline{B_s^0}$ Oscillation Frequency and the Ratio $|V_{td}/V_{ts}|$ at CDF

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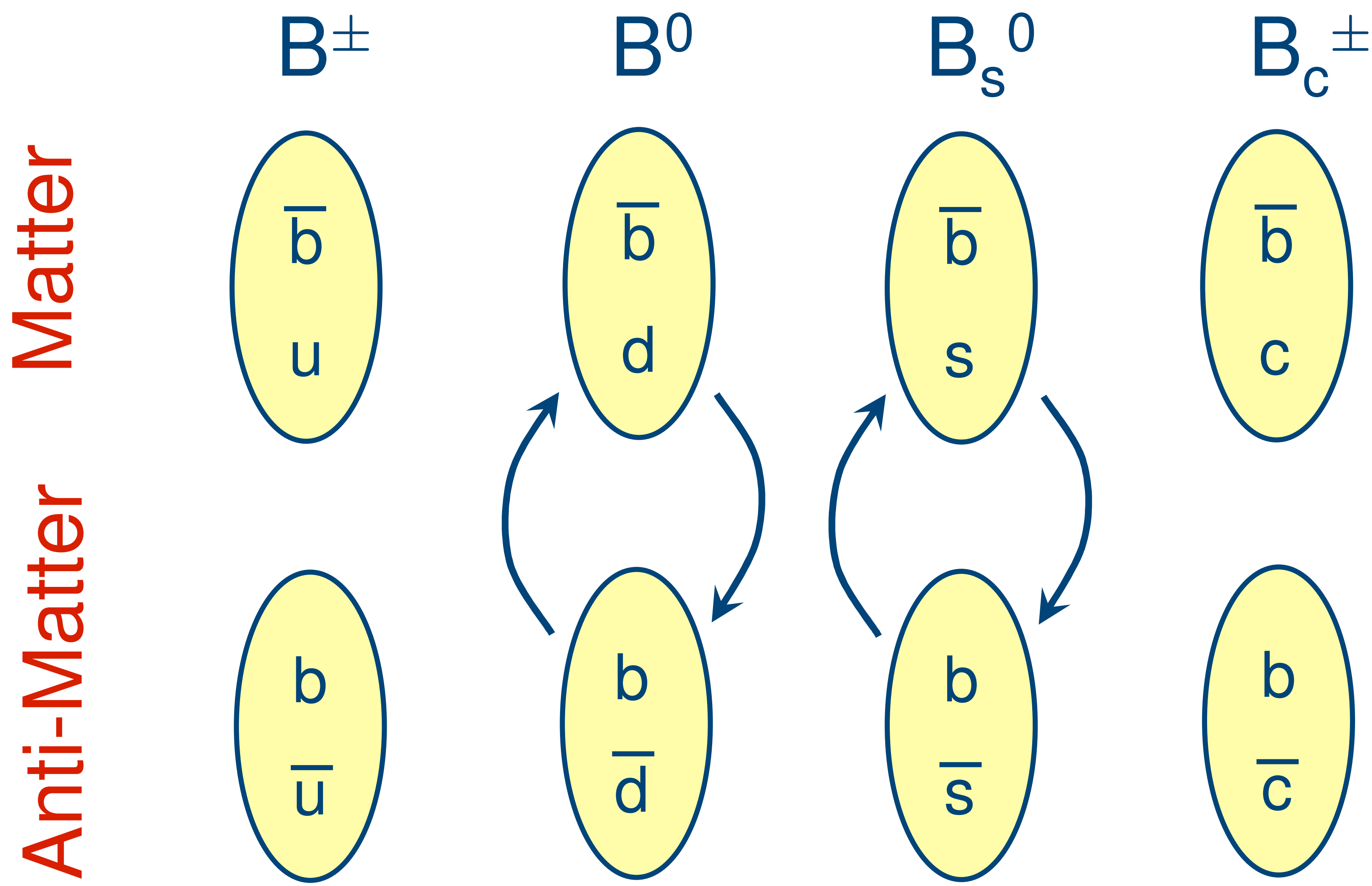
for the CDF Collaboration

B Mesons



$B^{\pm}$
B^{0}
B_s^{0}
$B_c^{\pm}$
Matter
$\bar{b}$
u
$\bar{b}$
d
$\bar{b}$
s
$\bar{b}$
c
Anti-Matter
b
$\bar{u}$
b
$\bar{d}$
b
$\bar{s}$
b
$\bar{c}$

B Mixing

- Neutral B Meson system

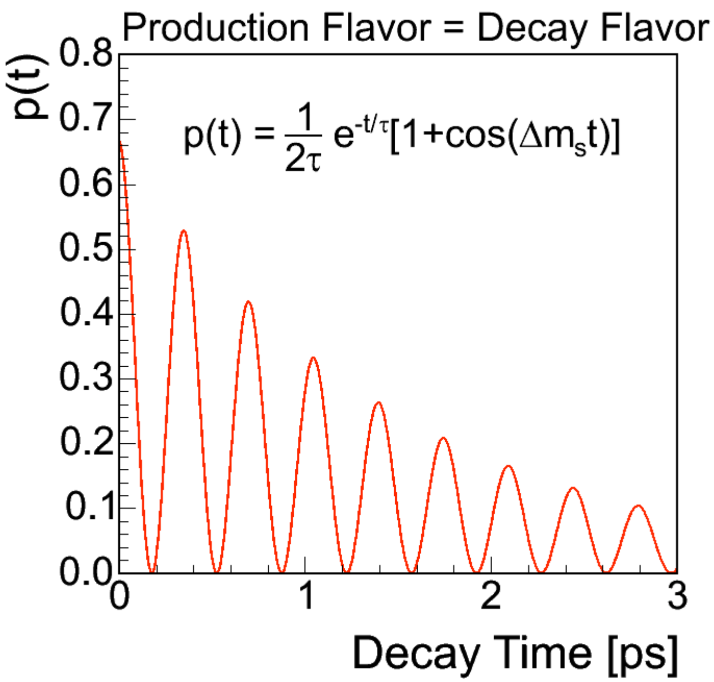
$$|B>=(\bar{b}s);\,|\overline{B}>=(b\bar{s})$$

mixture of two mass eigenstates (No CP violation case):

$$|B_H\rangle=\frac{1}{\sqrt{2}}\left(|B\rangle+|\overline{B}\rangle\right)$$

$$|B_L\rangle=\frac{1}{\sqrt{2}}\left(|B\rangle-|\overline{B}\rangle\right)$$

- B_H and B_L may have different mass and decay width
  - $\Delta m = M_H - M_L$ (>0 by definition)
  - $\Delta\Gamma = \Gamma_H - \Gamma_L$



- The case of $\Delta\Gamma = 0$

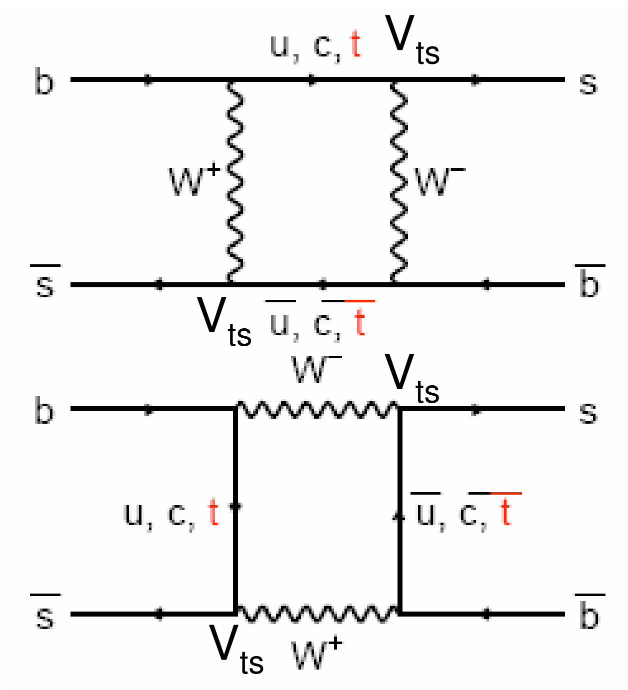
$$p(B\to B)=\frac{e^{-t/\tau}}{2\tau}(1+\cos\Delta mt)$$

$$p(B\to\overline{B})=\frac{e^{-t/\tau}}{2\tau}(1-\cos\Delta mt)$$

Standard Model Prediction

CKM Matrix — Wolfenstein parameterization

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$



Ratio of frequencies for B^0 and B_s

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \frac{f_{Bs}^2 B_{Bs}}{f_{Bd}^2 B_{Bd}} \frac{|V_{ts}|^2}{|V_{td}|^2} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

$\xi = 1.210 ^{+0.047}_{-0.035}$ from lattice QCD

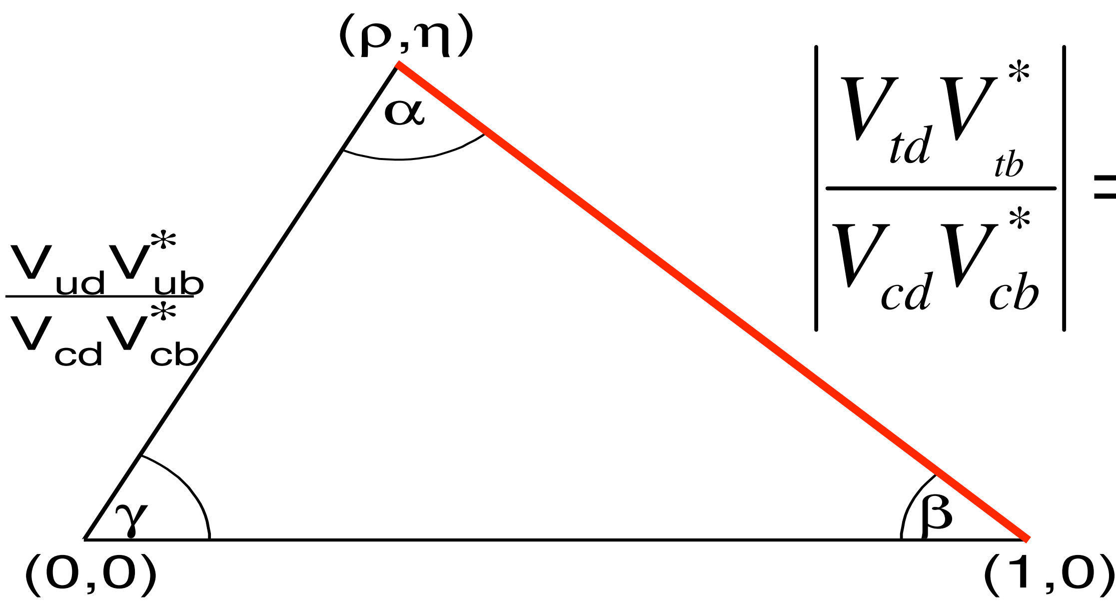
(hep/lat-0510113)

$V_{ts} \sim \lambda^2$, $V_{td} \sim \lambda^3$, $\lambda = 0.224 \pm 0.012$

Unitarity Triangle

CKM Matrix Unitarity Condition

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

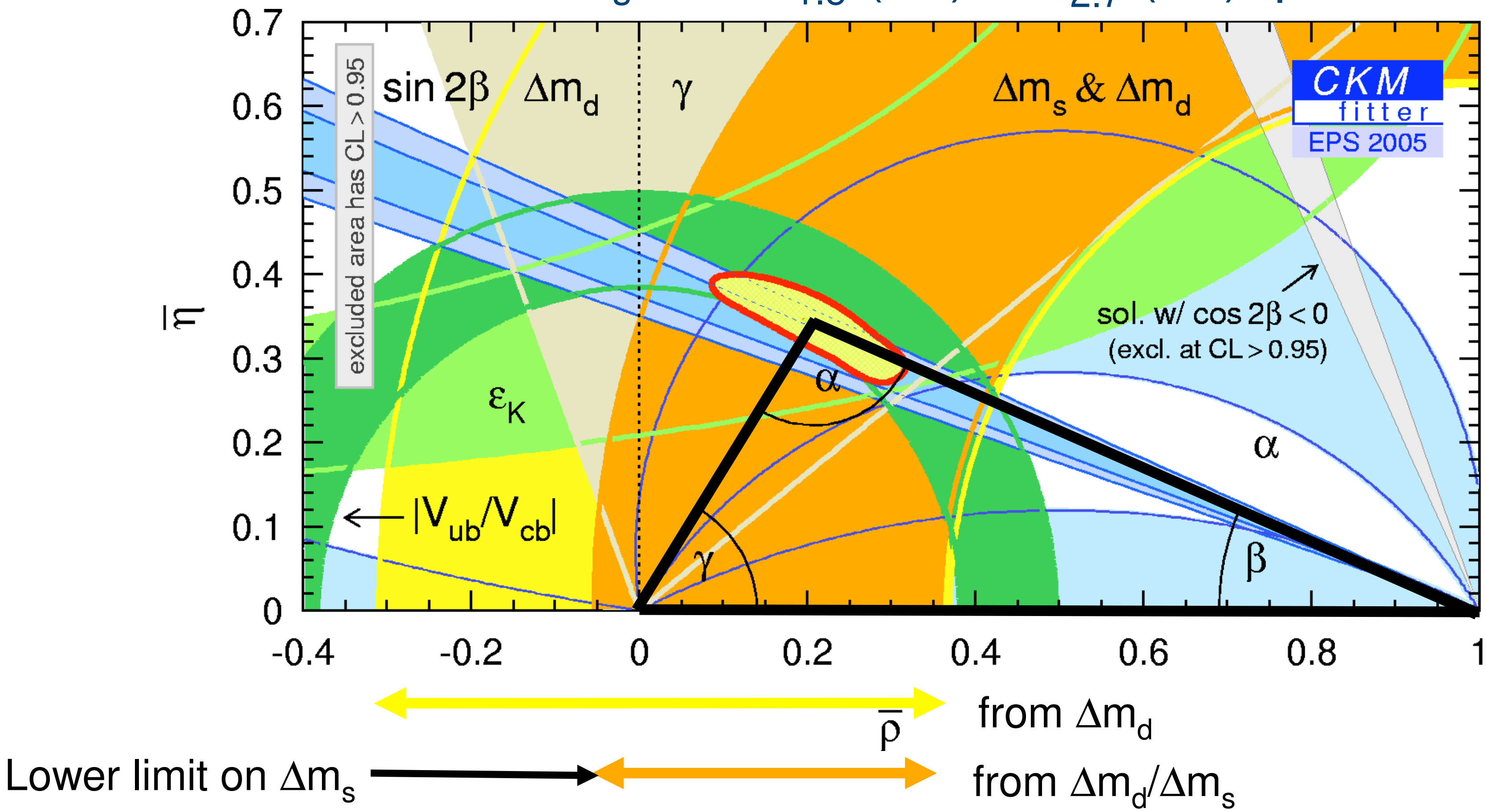


$$\left|\frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}}\right| = \frac{|V_{td}|}{|V_{ts}|} \times \frac{1}{|V_{cd}|}$$

$$\sim \sqrt{\frac{\Delta m_d}{\Delta m_s}}$$

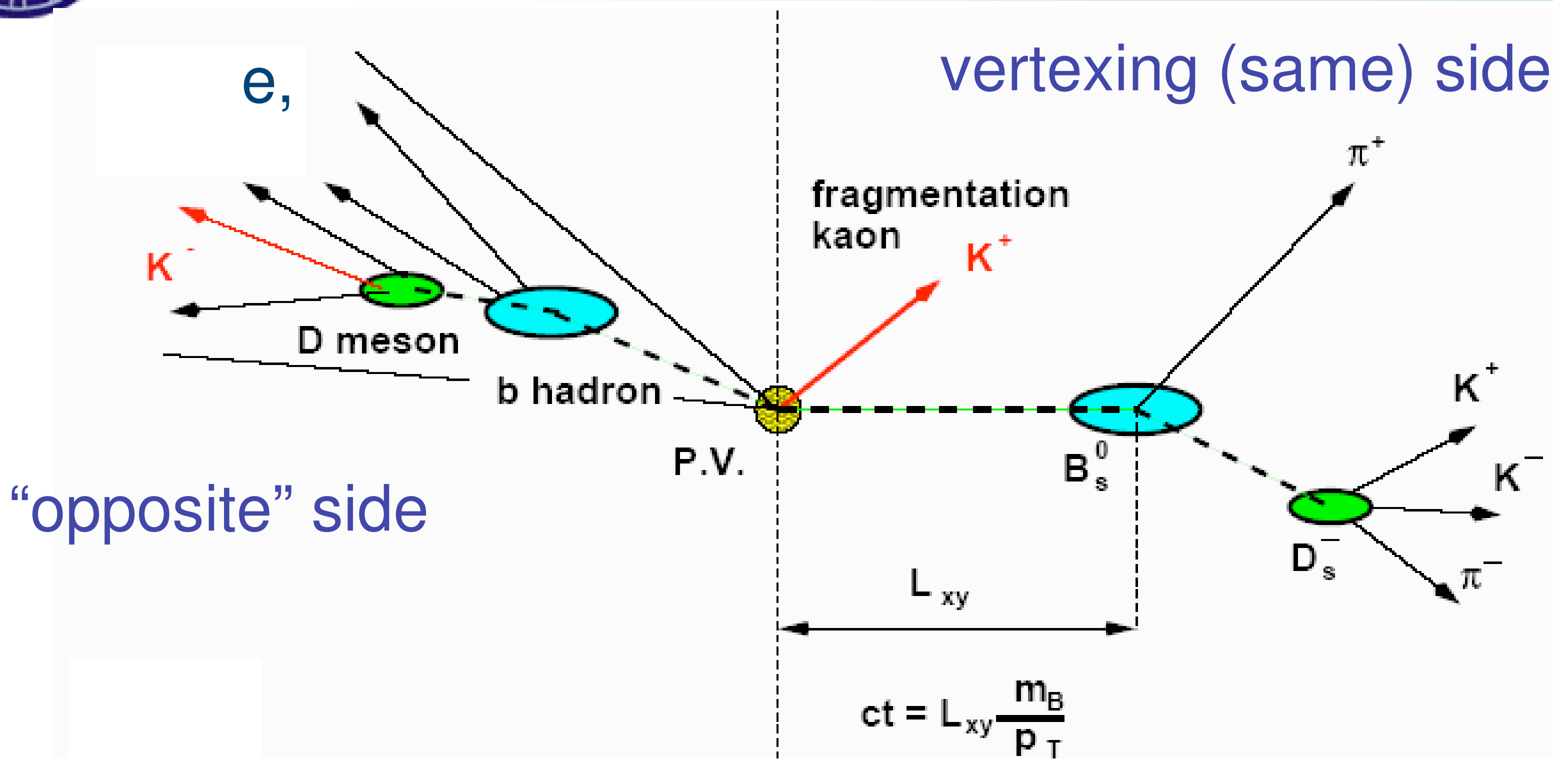
Unitarity Triangle Fit

- just for illustration, other fits exist
- CKM Fit result: Δm_s: $18.3^{+6.5}_{-1.5}$ (1σ) : $^{+11.4}_{-2.7}$ (2σ) ps^{-1}



Measurement Principle

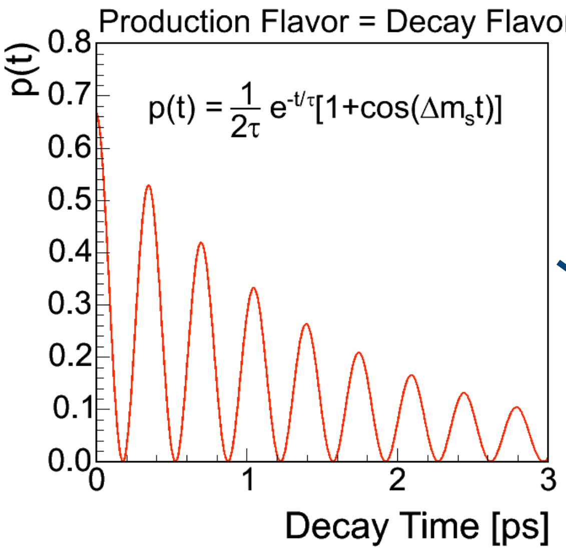
The “Big” Picture



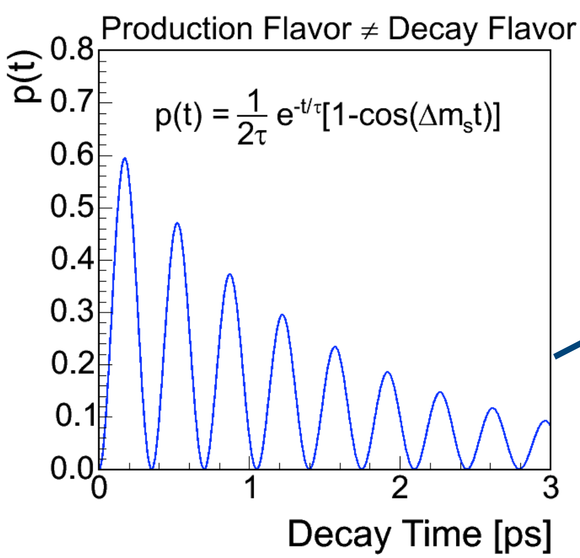
- reconstruct B_s decays $\rightarrow$ decay flavor from decay products
- measure proper time of the decay (very precisely)
- infer B_s production flavor (production flavor tagging)

Measurement .. In a Perfect World

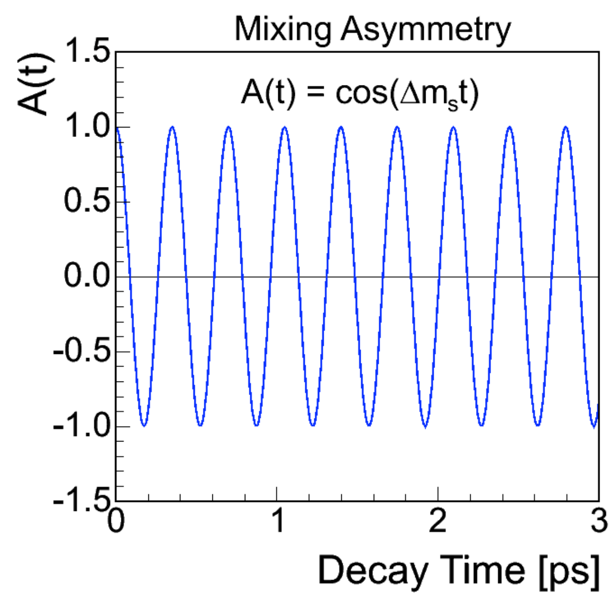
"Right Sign"



"Wrong Sign"



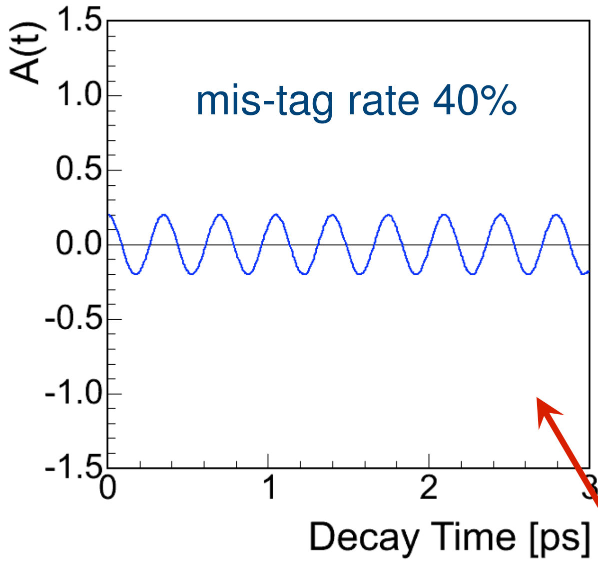
$$A(t) = \frac{N_{RS} - N_{WS}}{N_{RS} + N_{WS}}$$



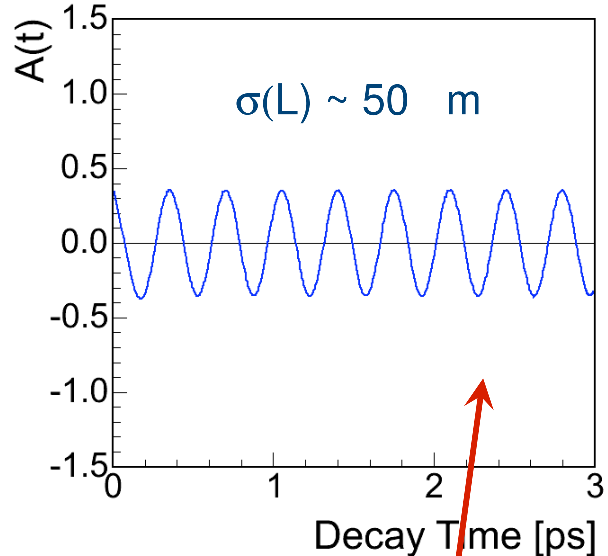
what about detector effects?

Realistic Effects

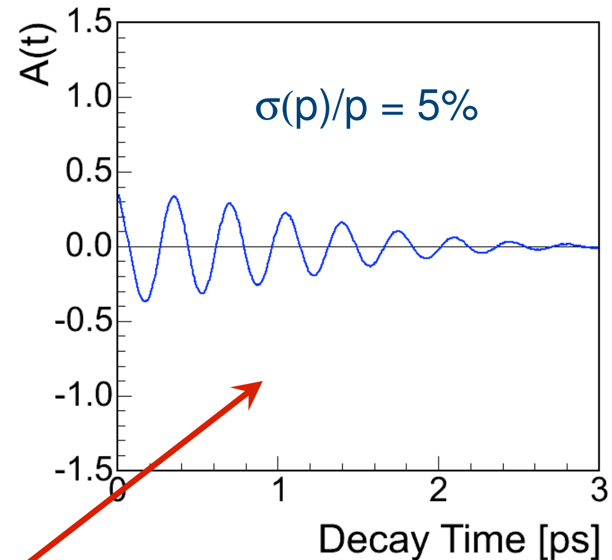
flavor tagging power, background



displacement resolution

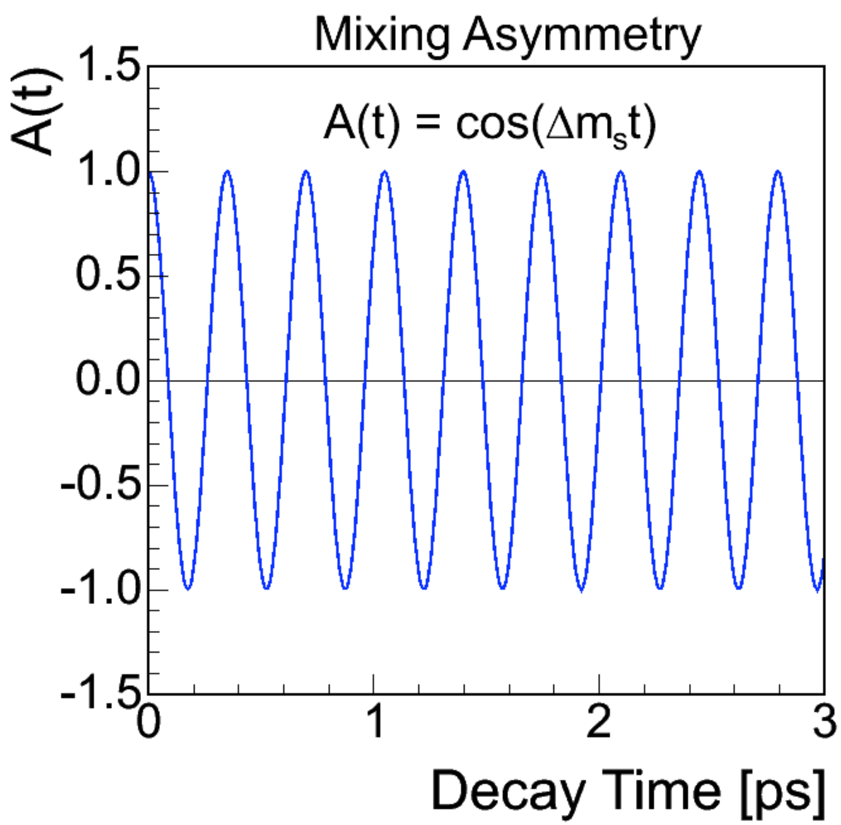


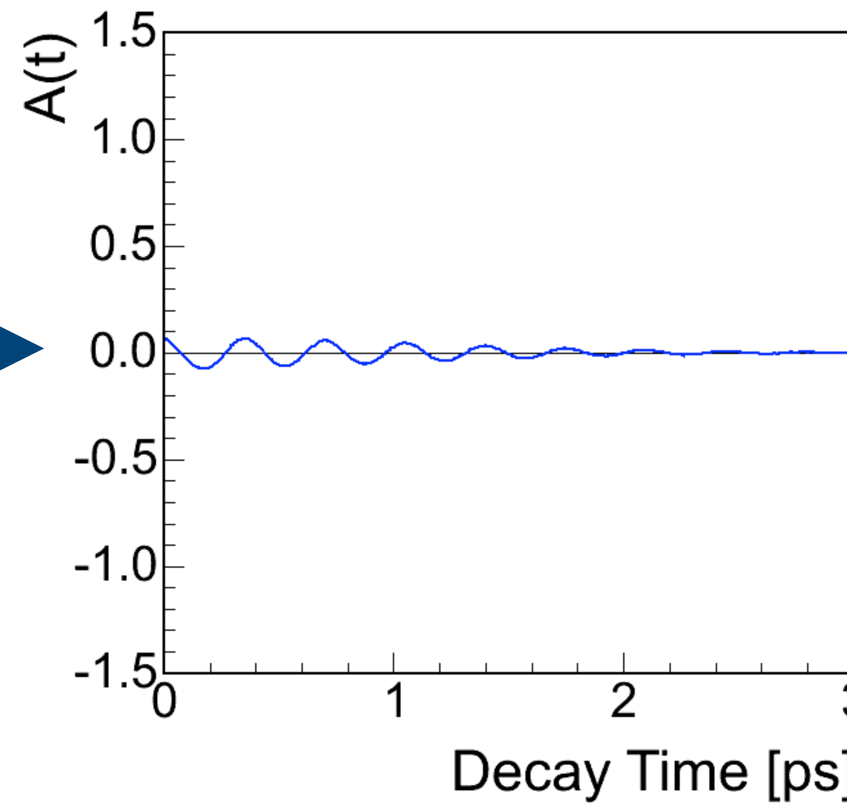
momentum resolution



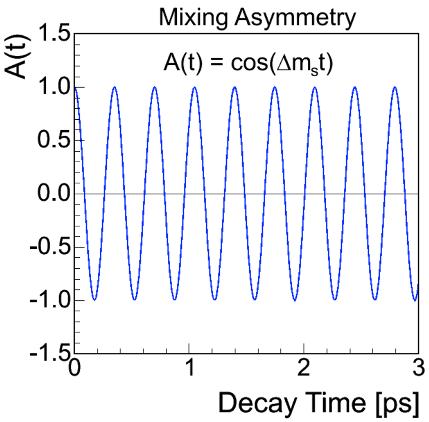
$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2}}\, e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

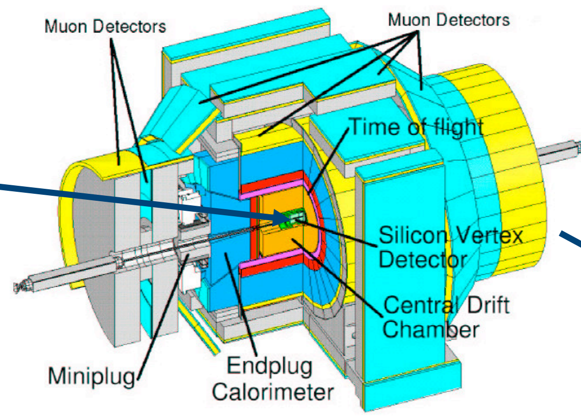
All Effects Together



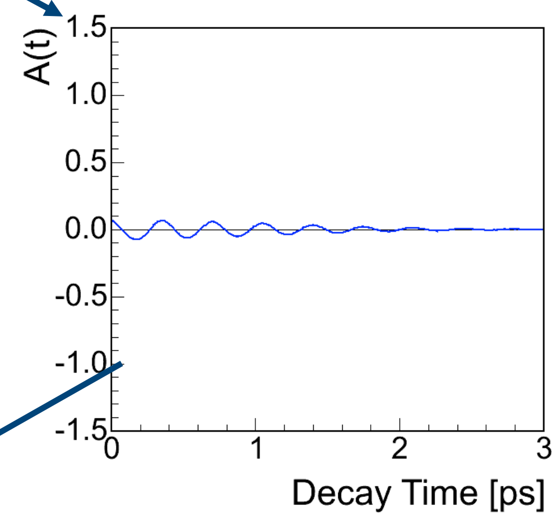


Real Measurement Layout





Data



momentum resolution
displacement resolution
flavor tagging power

scan for signal:

$A(\Delta m_s = 15\ ps^{-1}) = ?$

Unbinned Likelihood Fitter

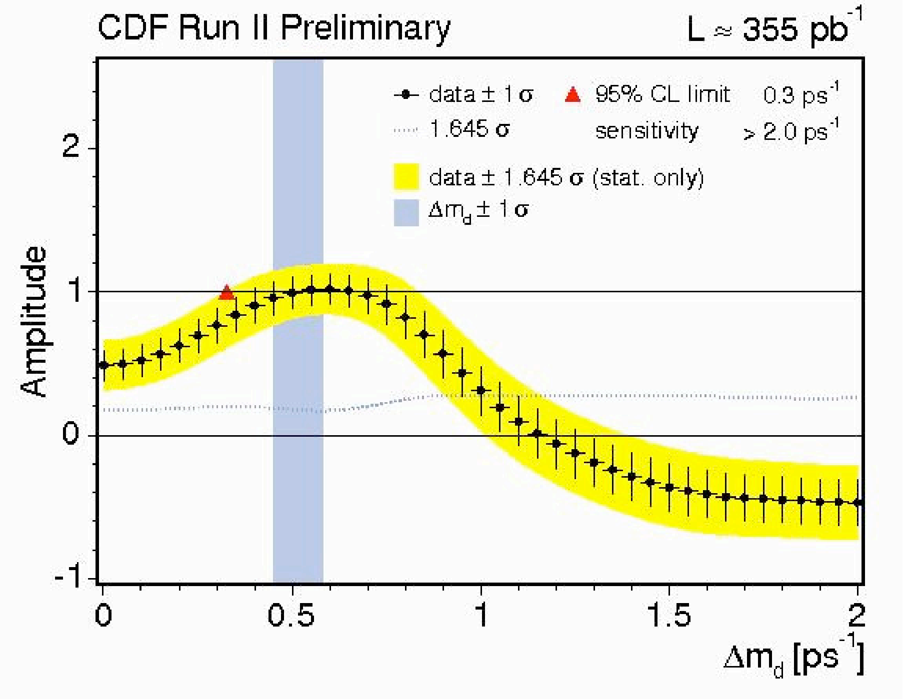
$p \sim e^{-t/\tau}[1 \pm AD \cos\Delta mt] \otimes R(t)$

measure frequency:

$\Delta m_s = ?$

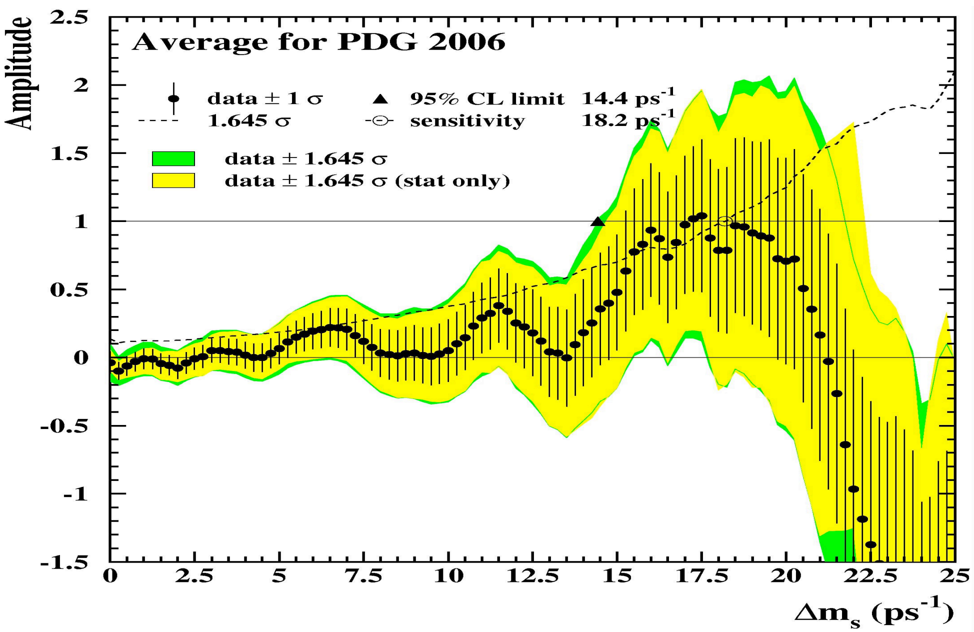
Scanning for Signals

$B^0 \rightarrow D^- \pi^+$

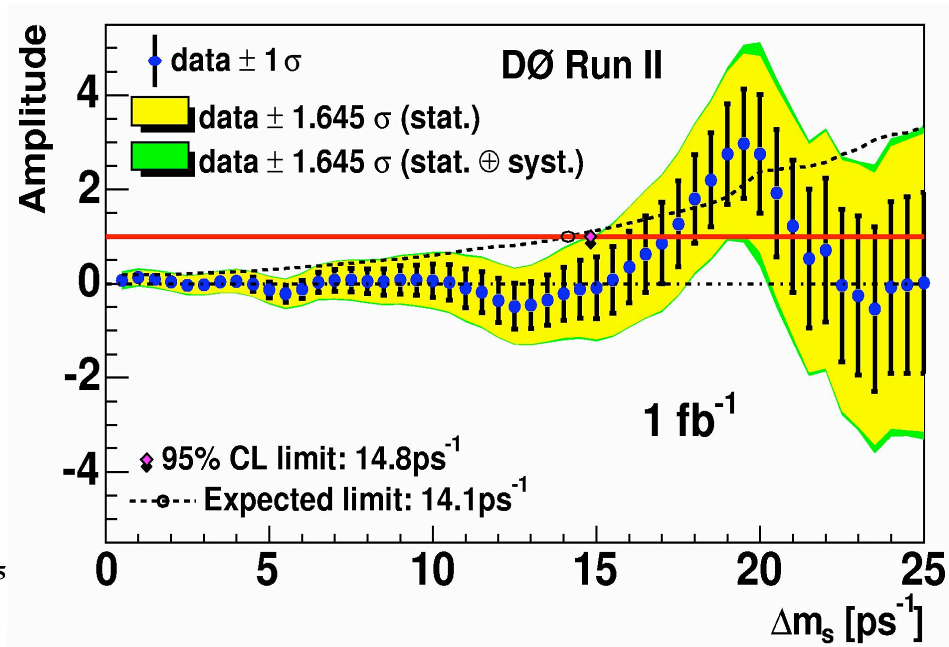


- fixed value of Δm_s, fit for Amplitude
- repeat for different values of Δm_s
- Signal: A ~ 1, Background: A ~ 0
- if a signal is found, fit for mixing frequency!

World Knowledge on Δm_s



PDG 2006



Recent D0 Result

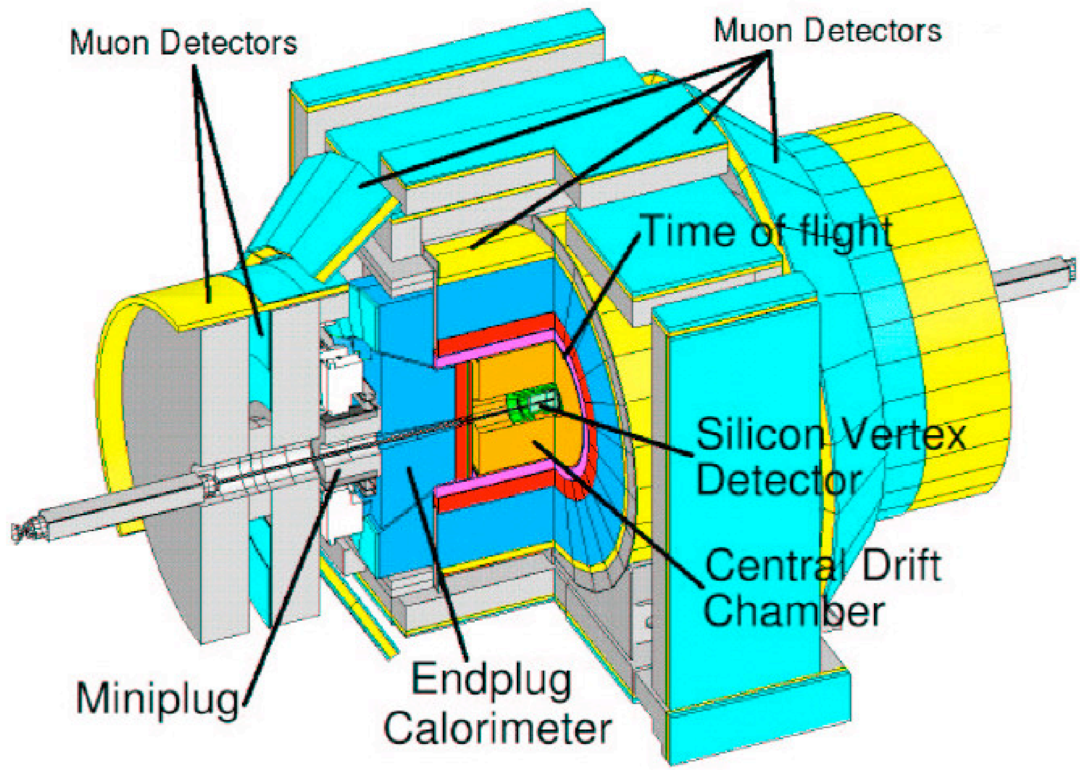
Samples of B_s Decays

The CDFII Detector

- multi-purpose detector
- excellent momentum resolution $\sigma(p)/p<0.1\%$

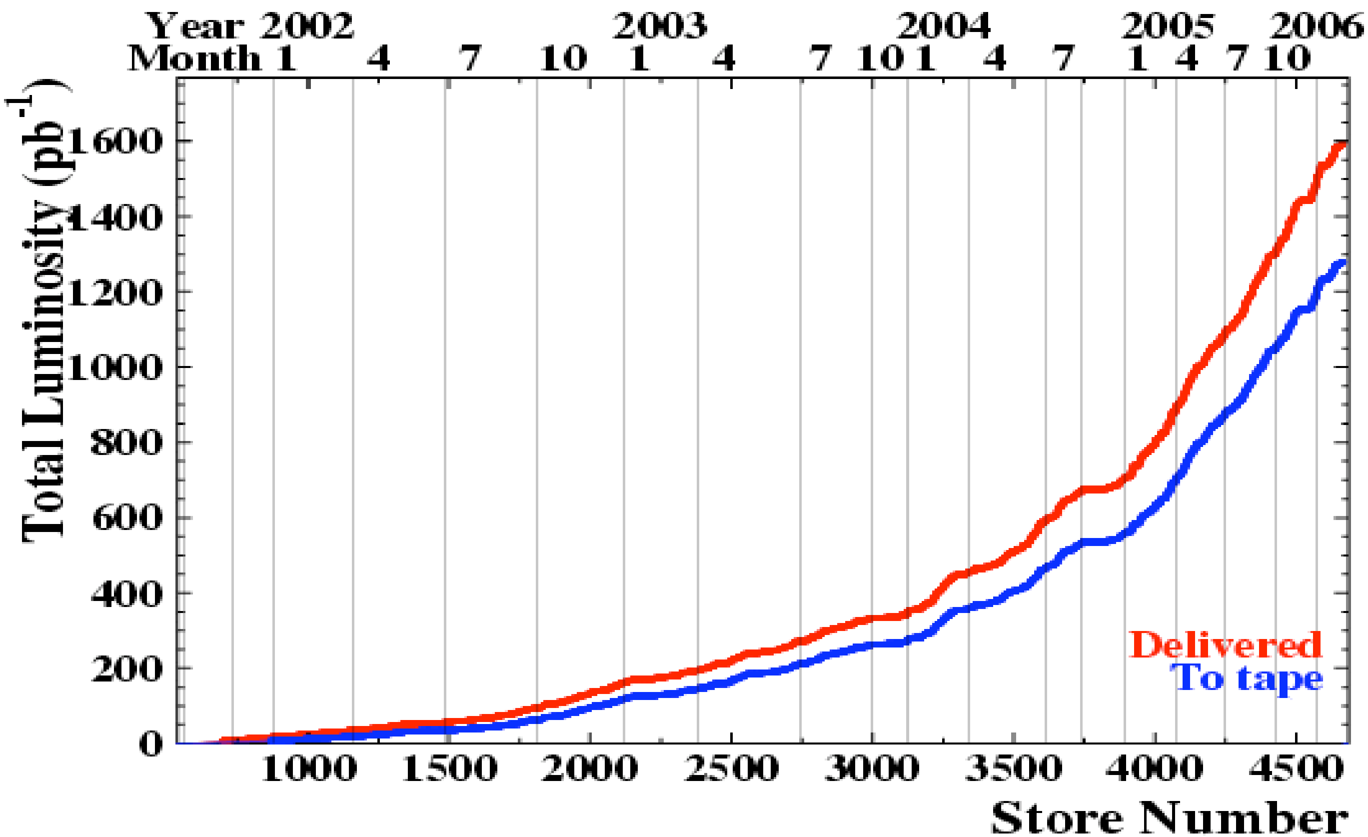
- Yield:
  - SVT based triggers
- Tagging power:
  - TOF, dE/dX in COT
- Proper time resolution:
  - SVXII, L00

CDF II Detector



Tevatron Luminosity

“Data Taking Period 1” “2” “3”



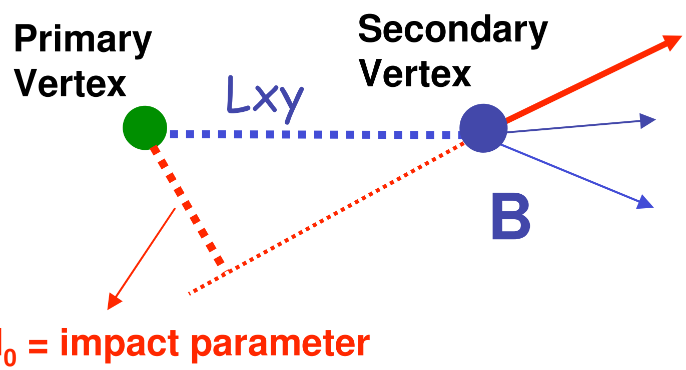
This analysis: Feb 2002 – Jan 2006 → 1 fb^{-1}

Celebration of the first 1 fb Delivered to CDF!

Thank You Accelerator Division

Triggering On Displaced Tracks

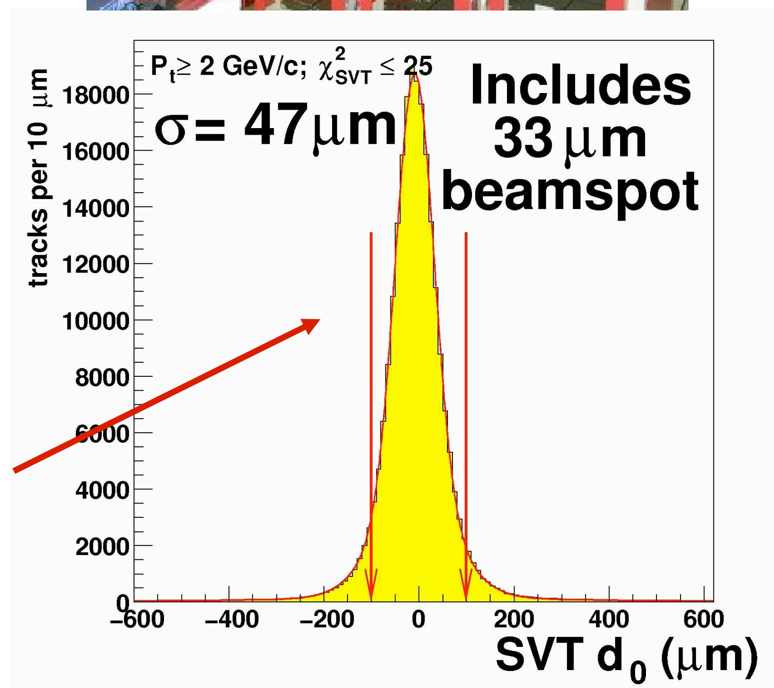
- trigger $B_s \to D_s^- \pi$, $B_s \to D_s^- l^+$



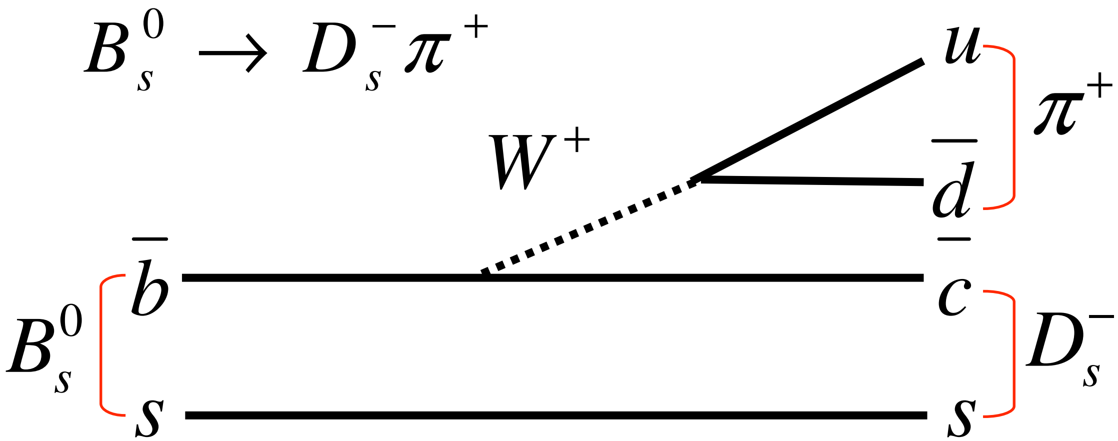
- trigger extracts 20 TB /sec
- “unusual” trigger requirement:
  - two displaced tracks:

($p_T > 2$ GeV/c, 120 m$<|d_0|<$1mm)

- requires precision tracking in SVX



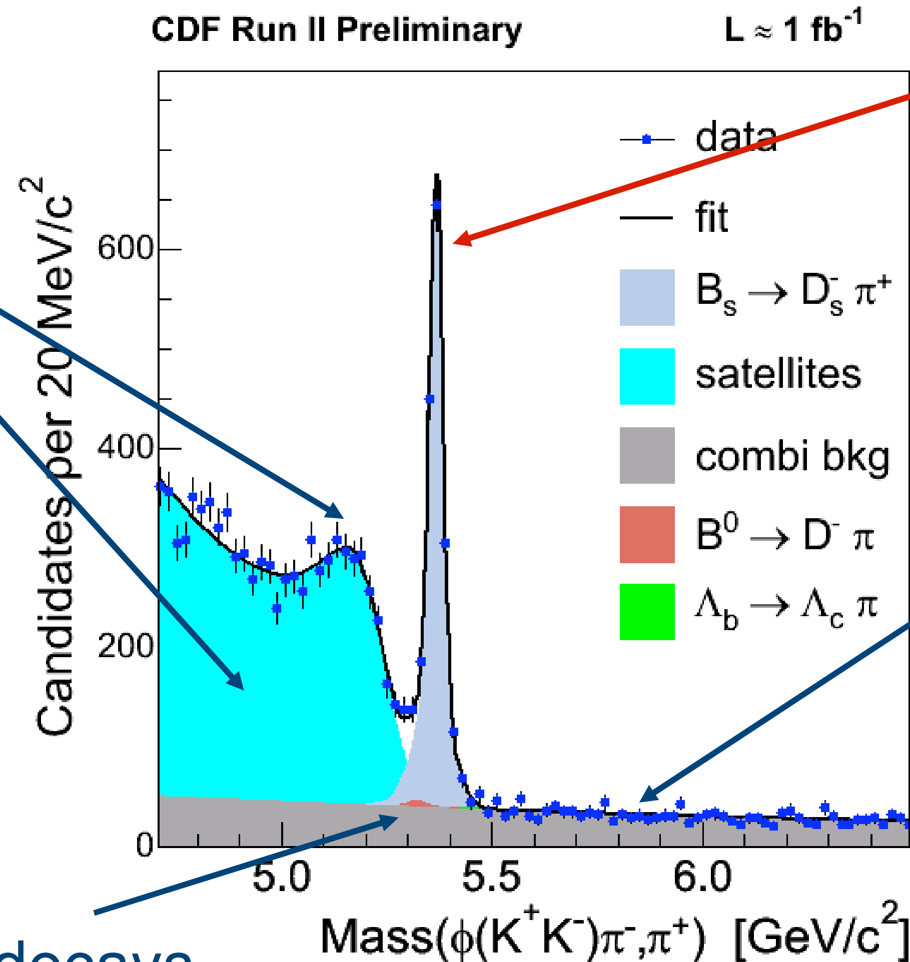
Hadronic B_s Decays



- relatively small signal yields (few thousand decays)
- momentum completely contained in tracker
- superior sensitivity at higher Δm_s

Example Mass Spectrum

partially reconstructed B mesons (satellites)



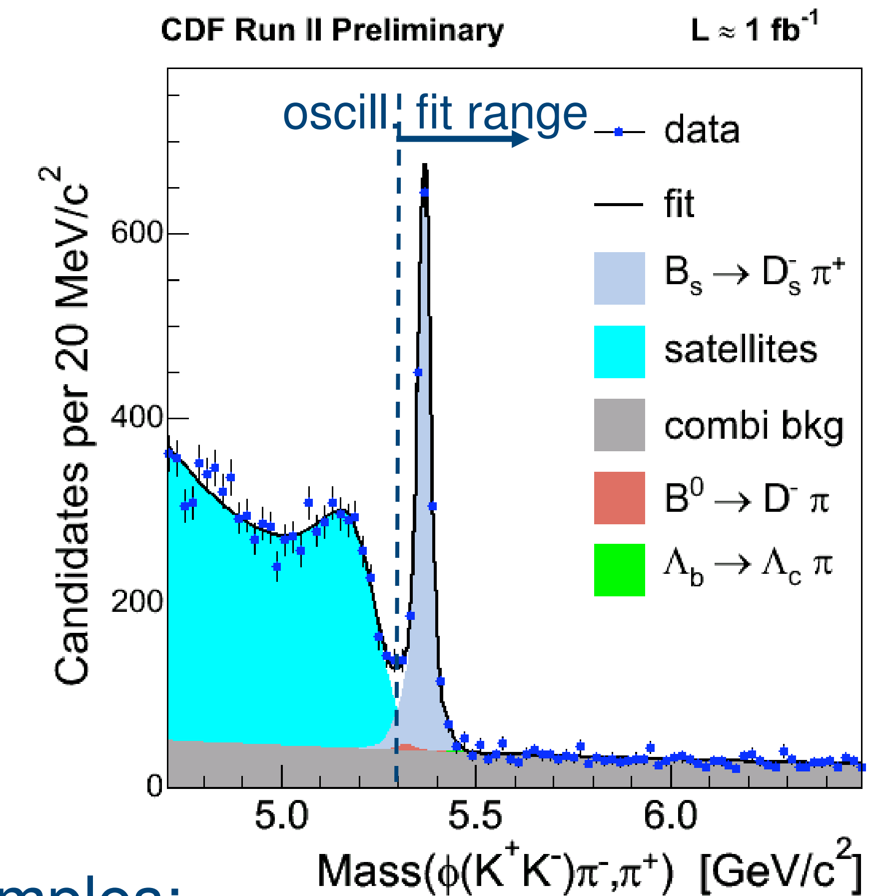
signal
$B_s \to D_s\pi$,
$D_s \to \phi\pi$,
$\phi \to K^+K^-$

combinatorial background

$B^0 \to D^-\pi$ decays

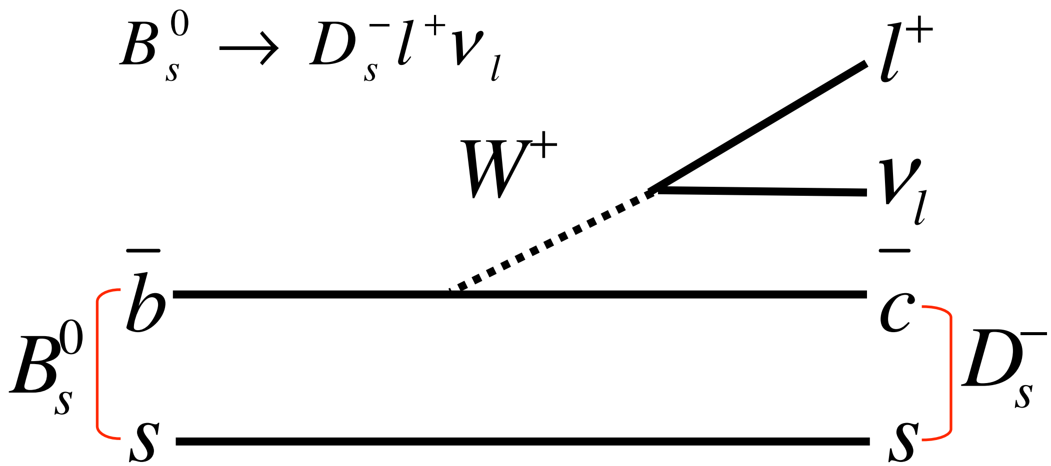
Signal Yield Summary: Hadronic

	Yield
$B_s \rightarrow D_s\pi\ (\phi\pi)$	1600
$B_s \rightarrow D_s\pi\ (K^* K)$	800
$B_s \rightarrow D_s\ \pi\ (3\pi)$	600
$B_s \rightarrow D_s 3\pi\ (\phi\ \pi)$	500
$B_s \rightarrow D_s 3\pi\ (K^* K)$	200
Total	3700



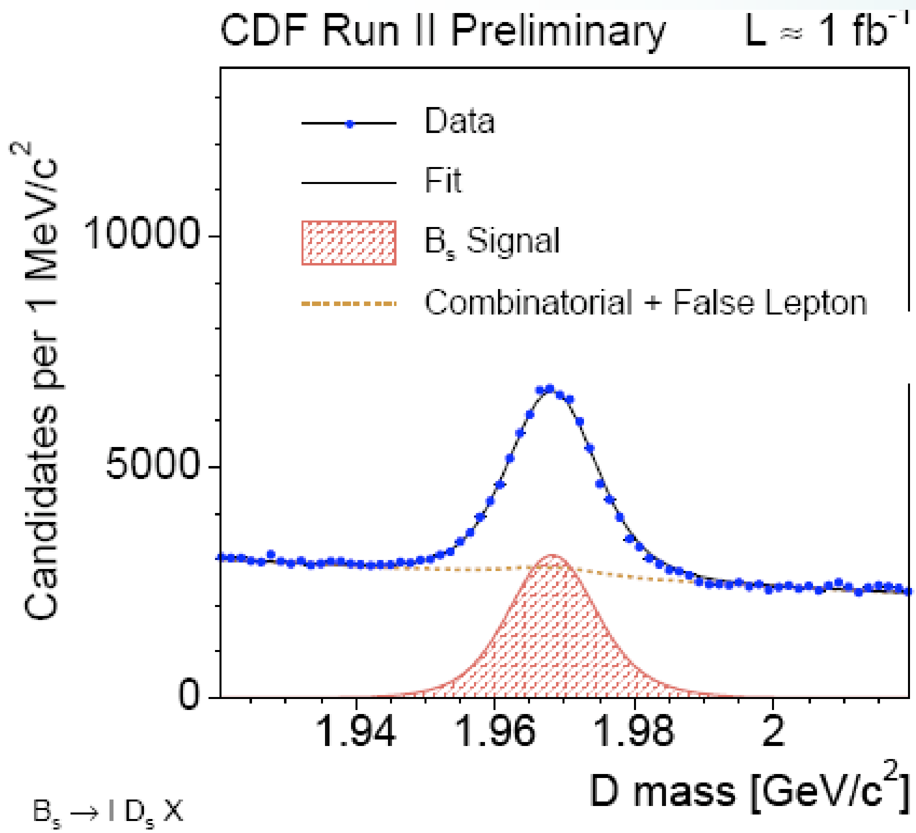
- high statistics light B meson samples:
  B^+ ($D^0\pi$): 26k events
  B^0 ($D^-\pi$): 22k events

Semileptonic B_s Decays



- relatively large signal yields (several 10’s of thousands)
- correct for missing neutrino momentum on average
- loss in proper time resolution
- superior sensitivity in lower Δm_s range

Semileptonic Samples: $D_s^- l^+ X$



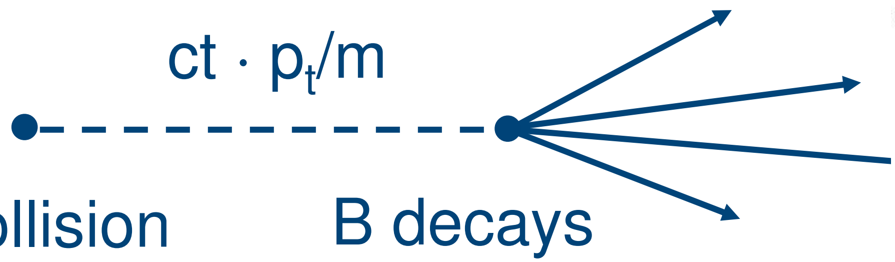
~53 K events

D_s: $D_s \rightarrow \phi\pi$	32 K
D_s: $D_s \rightarrow K^*K$	11 K
D_s: $D_s \rightarrow \pi\pi\pi$	10 K

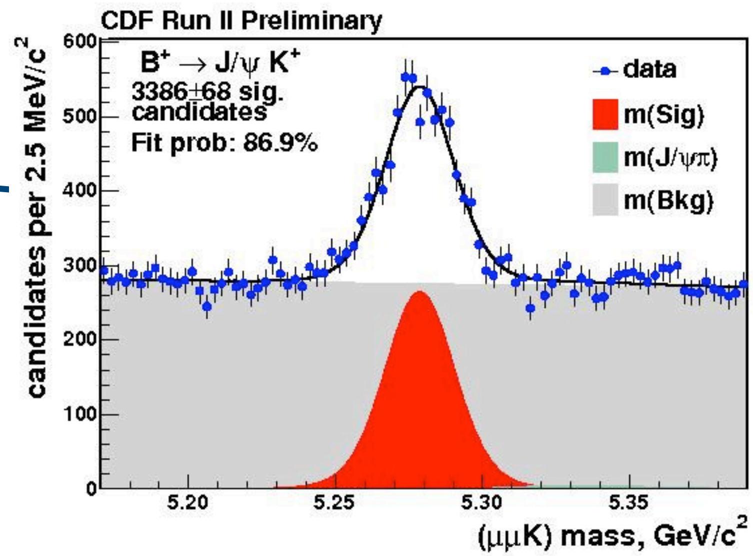
D^0: $D^0 \rightarrow K\pi$	540 K
D^{*-}: $D^0 \rightarrow K\pi$	75 K
D^-: $D^- \rightarrow K\pi\pi$	300 K

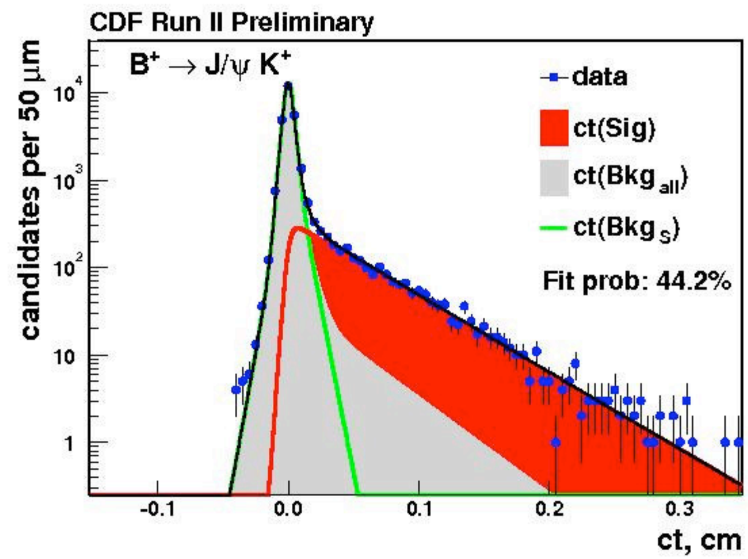
B Lifetime Measurements

“Classic” B Lifetime Measurement



- reconstruct B meson mass, p_T, L_{xy}
- calculate proper decay time (ct)
- extract $c\tau$ from combined mass+lifetime fit
- signal probability:
  $p_{signal}(t) = e^{-t'/\tau} \otimes R(t',t)$
- background $p_{bkgd}(t)$ modeled from sidebands

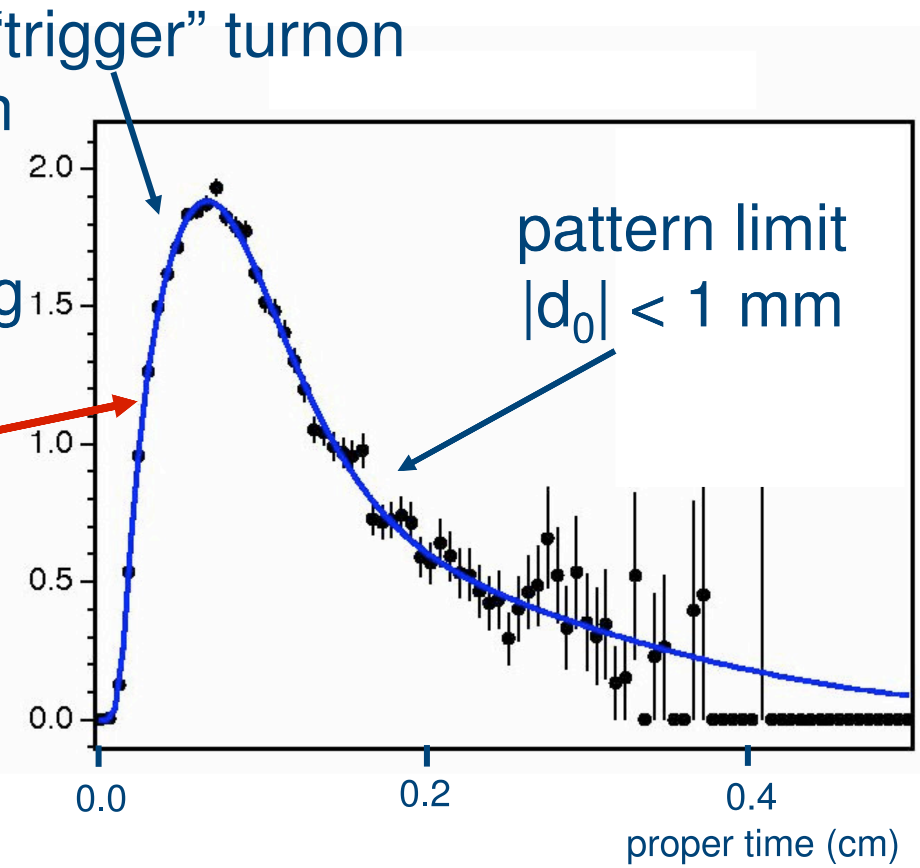




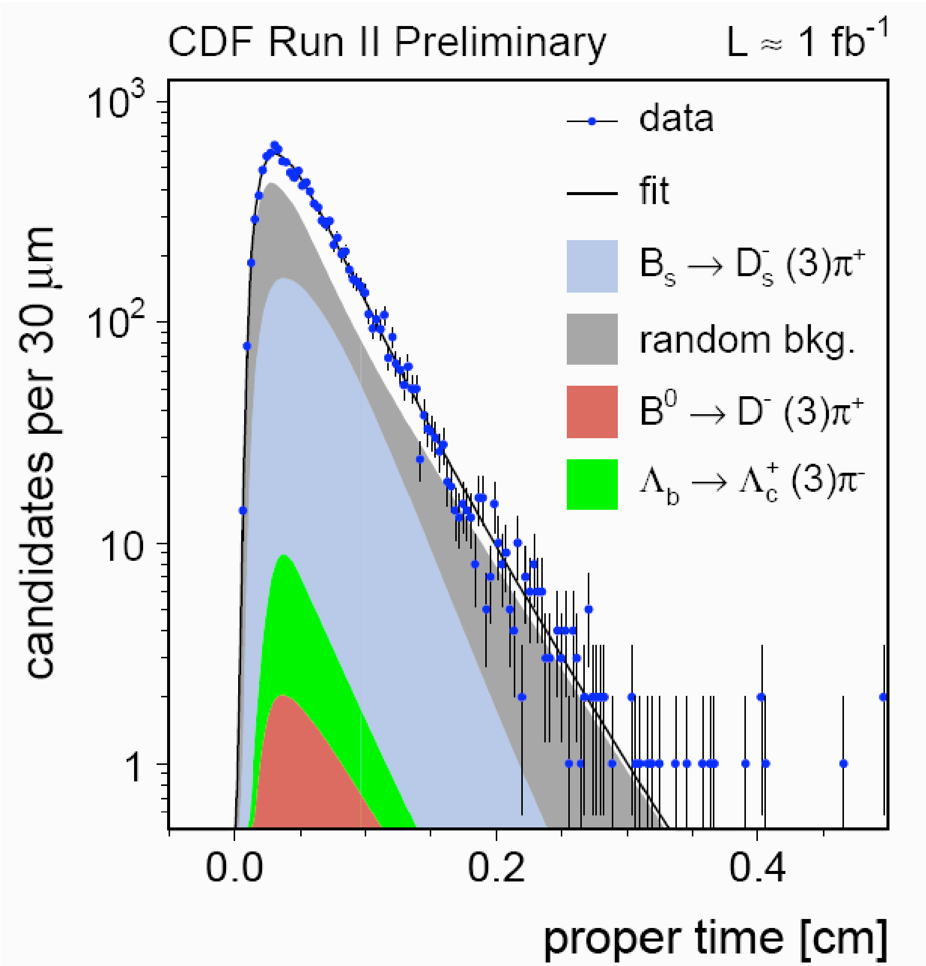
Hadronic Lifetime Measurement

- SVT trigger, event selection sculpts lifetime distribution
- correct for on average using efficiency function:

  $p = e^{-t'/\tau} \otimes R(t',t) \cdot \varepsilon(t)$
- efficiency function shape contributions:
  - event selection, trigger
- details of efficiency curve
  - important for lifetime measurement
  - inconsequential for mixing measurement



Hadronic Lifetime Results



Mode	Lifetime [ps] (stat. only)
$B^0 \to D^- \pi^+$	1.508 ± 0.017
$B^- \to D^0 \pi^-$	1.638 ± 0.017
$B_s \to D_s \pi(\pi\pi)$	1.538 ± 0.040

- World Average:

$B^0 \to 1.534 \pm 0.013$ ps^{-1}
$B^+ \to 1.653 \pm 0.014$ ps^{-1}
$B_s \to 1.469 \pm 0.059$ ps^{-1}

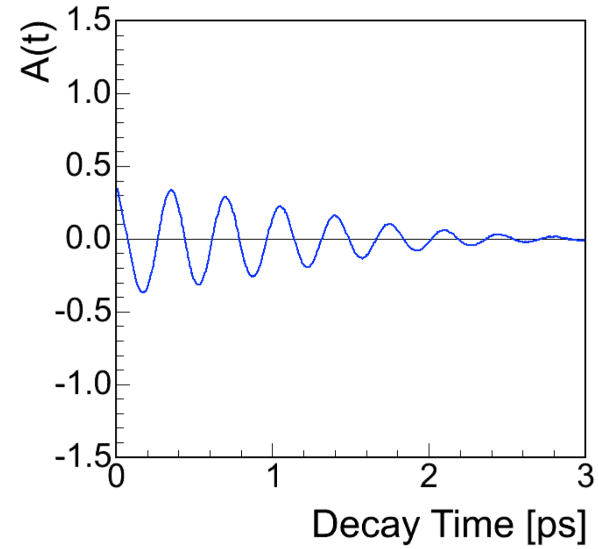
Excellent agreement!

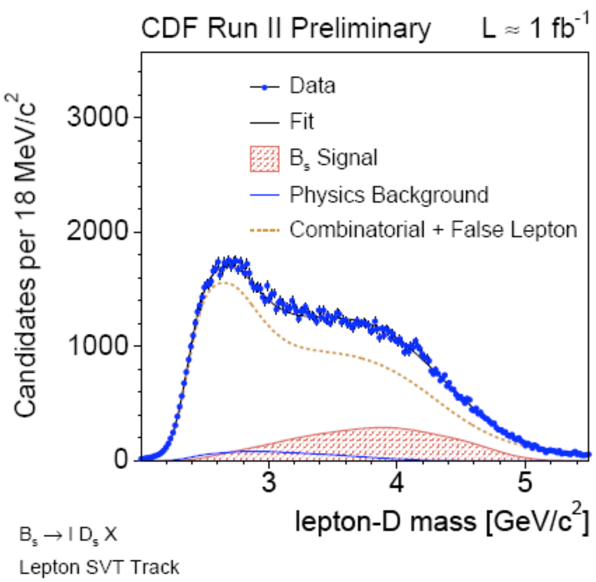
Semileptonic Lifetime Measurement

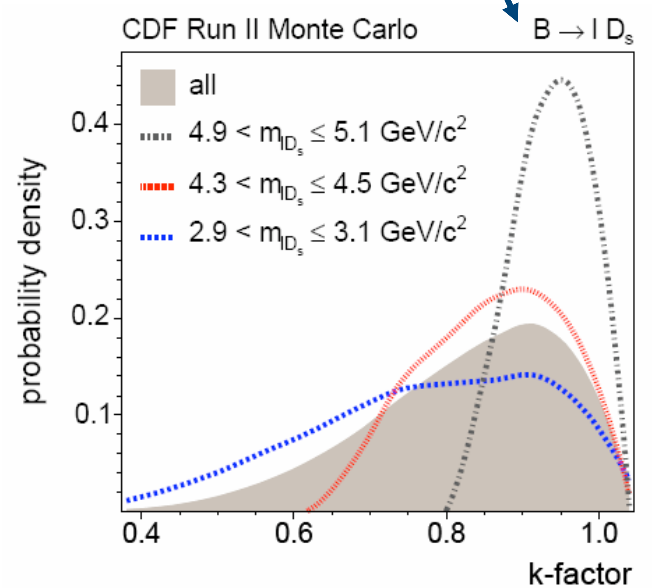
- neutrino momentum not reconstructed

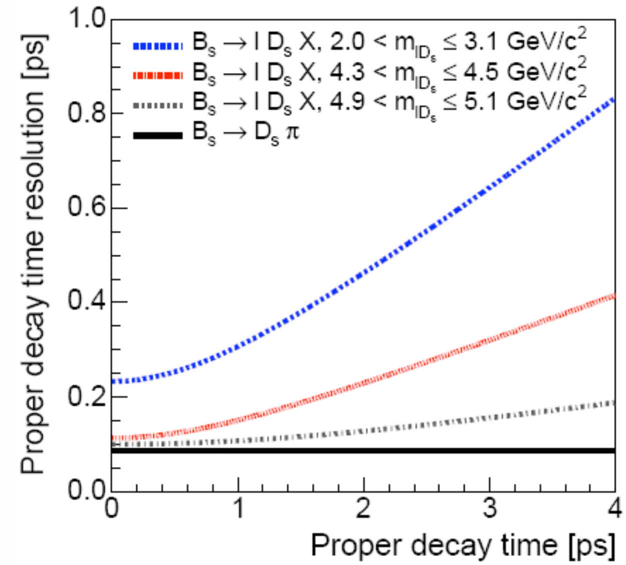
$$K = \frac{p_T(lD)}{p_T(B)} \cdot \frac{L(B)}{L(lD)}$$

- correct for neutrino on average

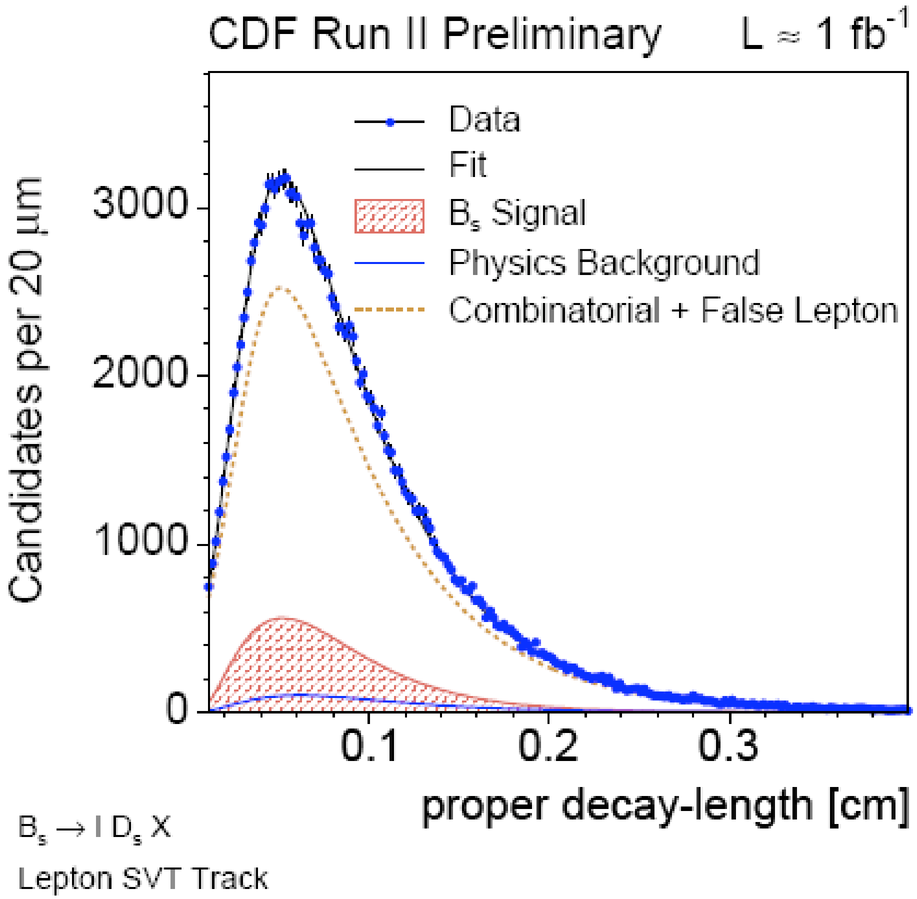




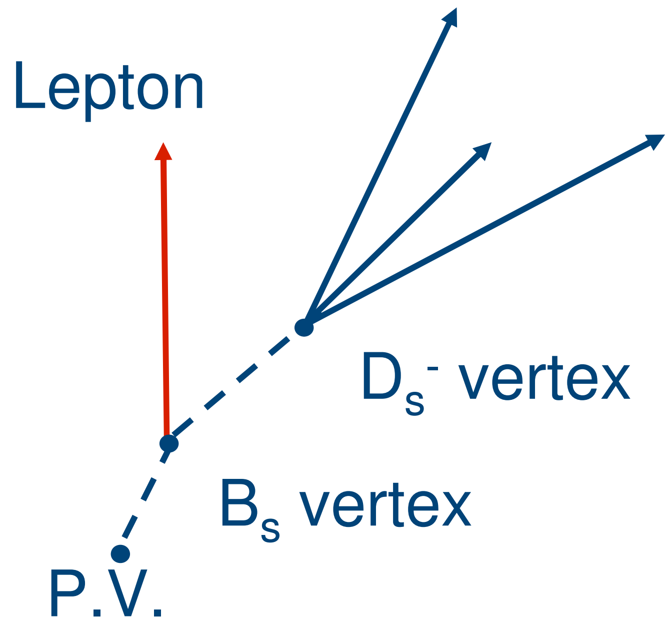




lD_s ct* Projections



$$ct^* = \frac{L(lD) \cdot m(B)}{p_T(lD)}$$



B_s lifetime in 355 pb^{-1}: 1.48 $\pm$ 0.03 (stat) ps

World Average value: 1.469 $\pm$ 0.059 ps

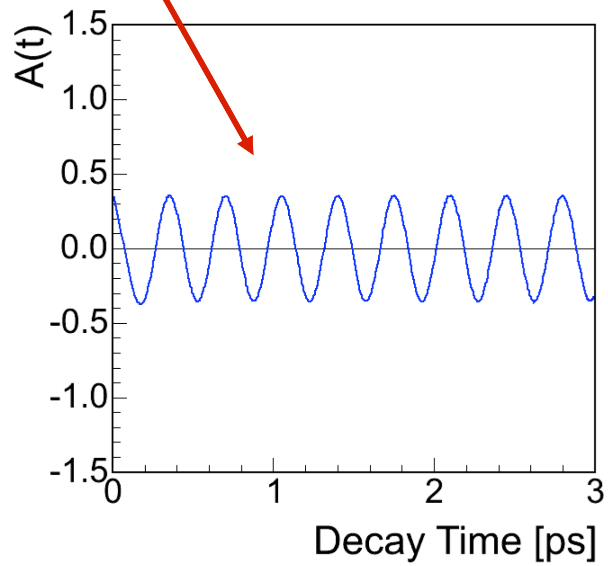
Proper Time Resolution

Proper Time Resolution

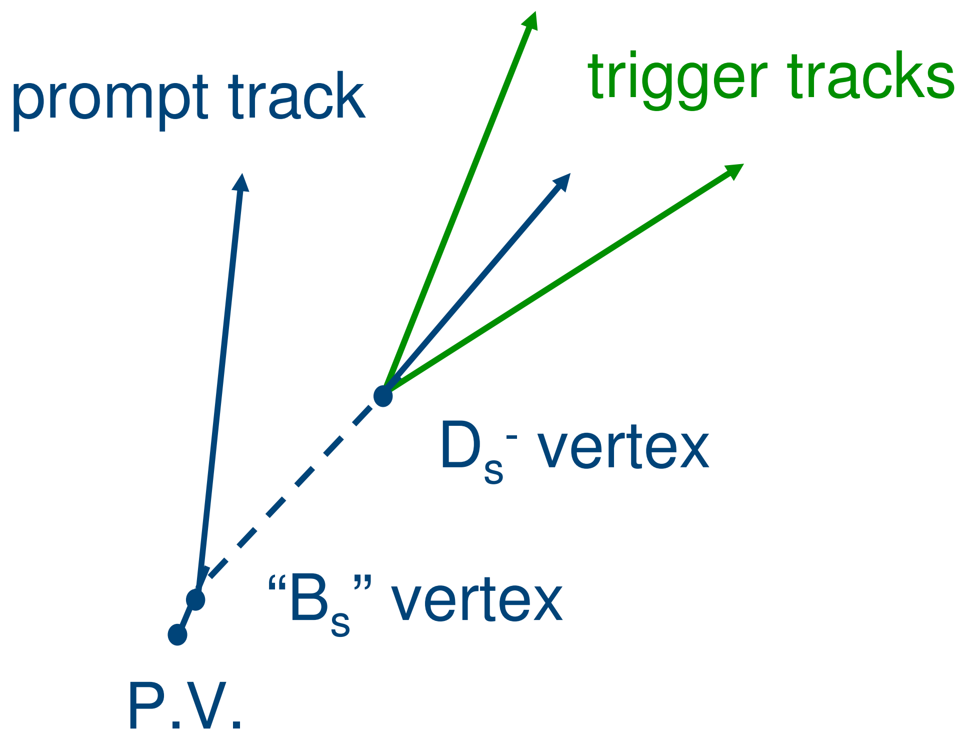
- Reminder, measurement significance:

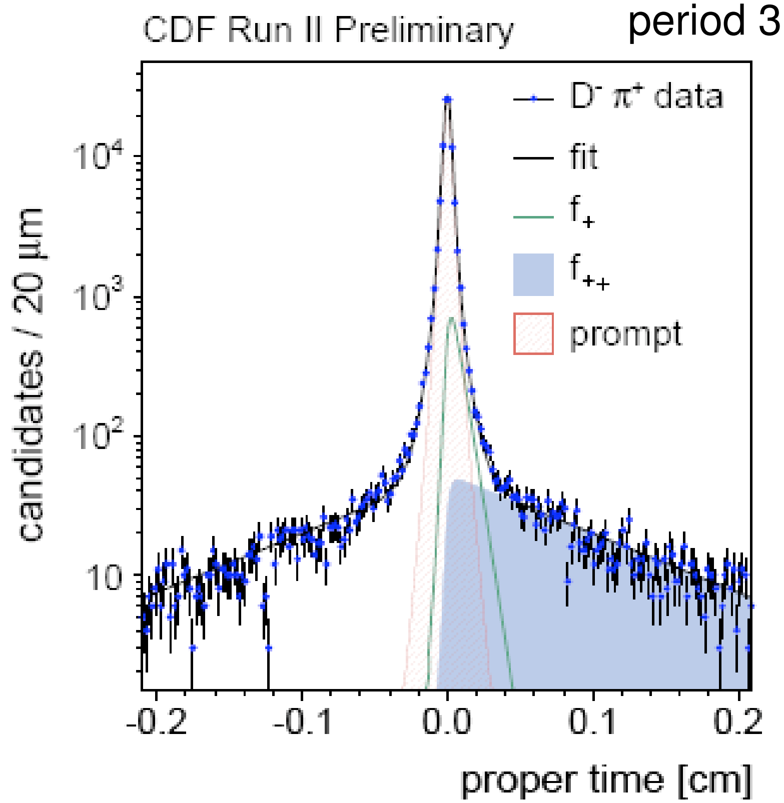
$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2}}\, e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

- significant effect
- fitter has to correctly account for it
- lifetime measurements not very sensitive to resolution
- a dedicated calibration is needed!



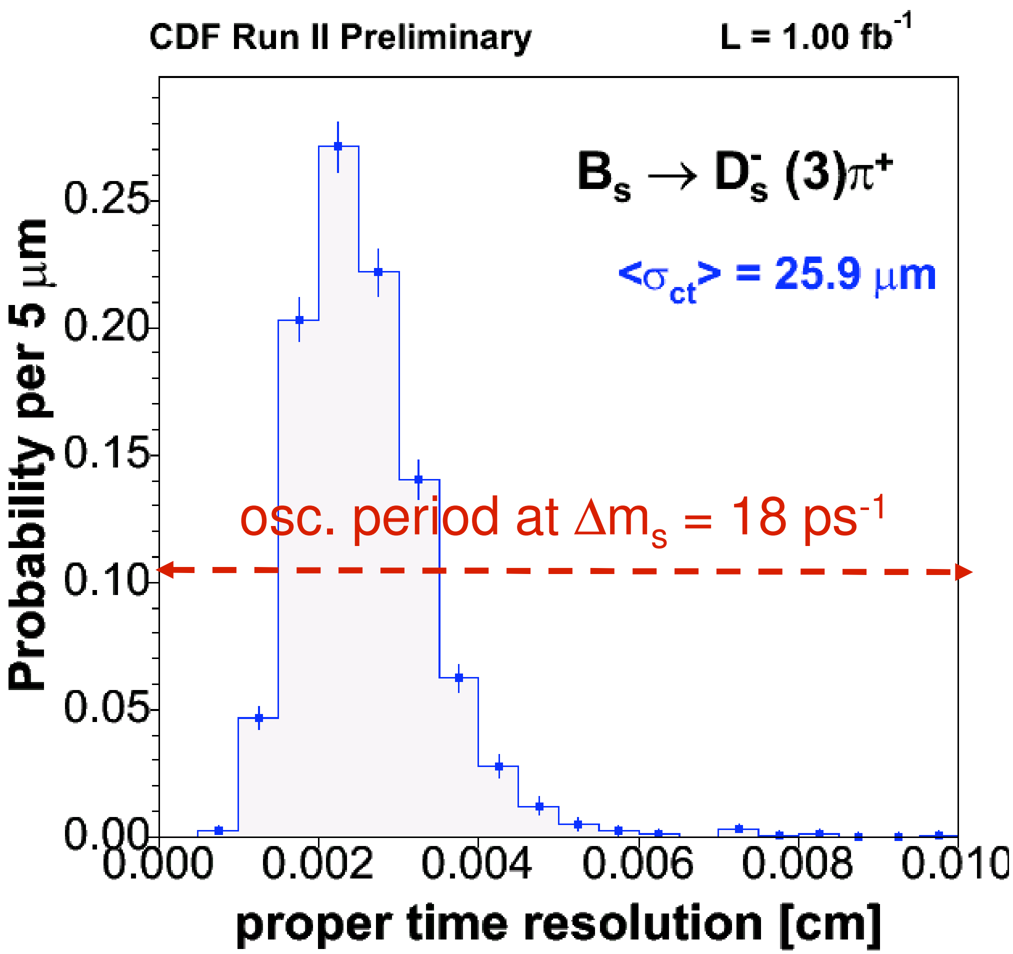
Calibrating the Proper Time Resolution





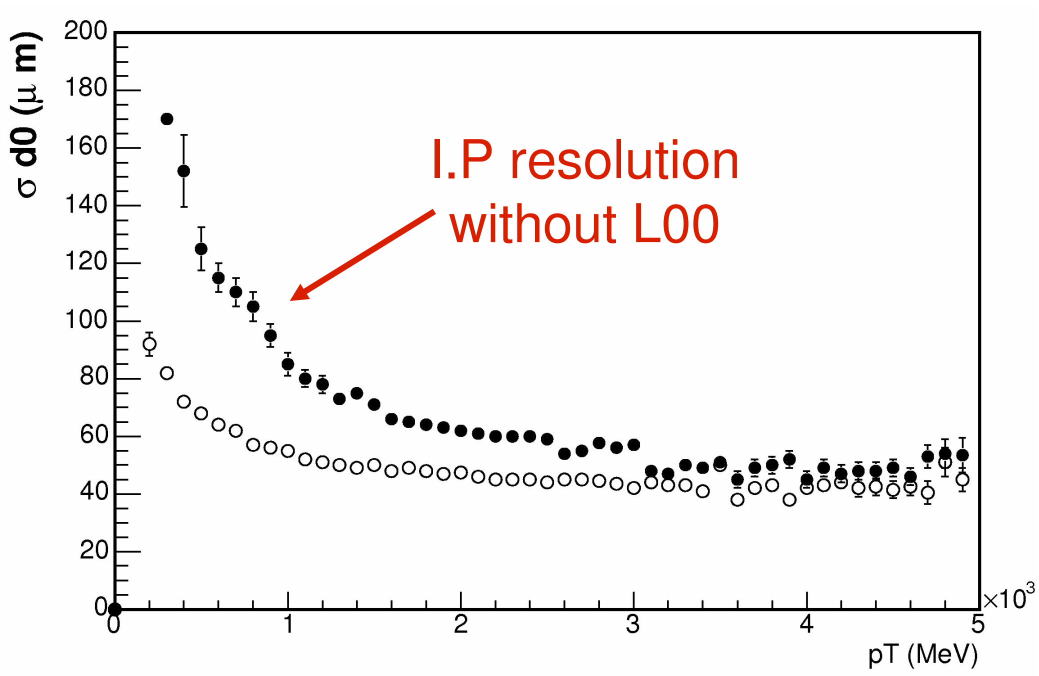
- utilize large prompt charm cross section
- construct "B^0-like" topologies of prompt D^- + prompt track
- calibrate ct resolution by fitting for "lifetime" of "B^0-like" objects

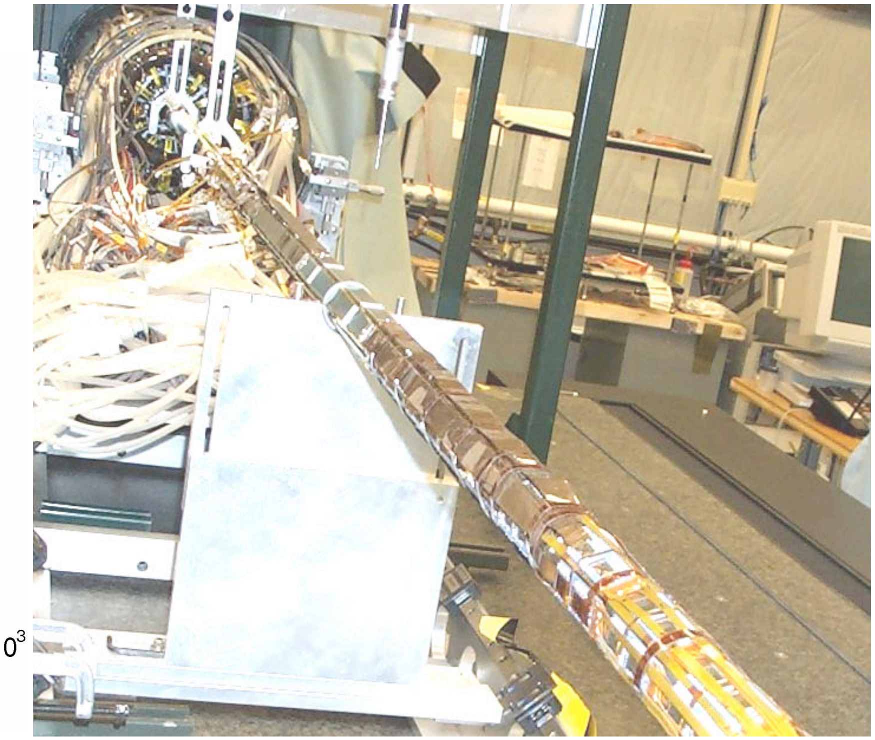
B_s Proper Time Resolution



- event by event determination of primary vertex position used
- average uncertainty ~ 26 m
- this information is used per candidate in the likelihood fit

Layer "00"

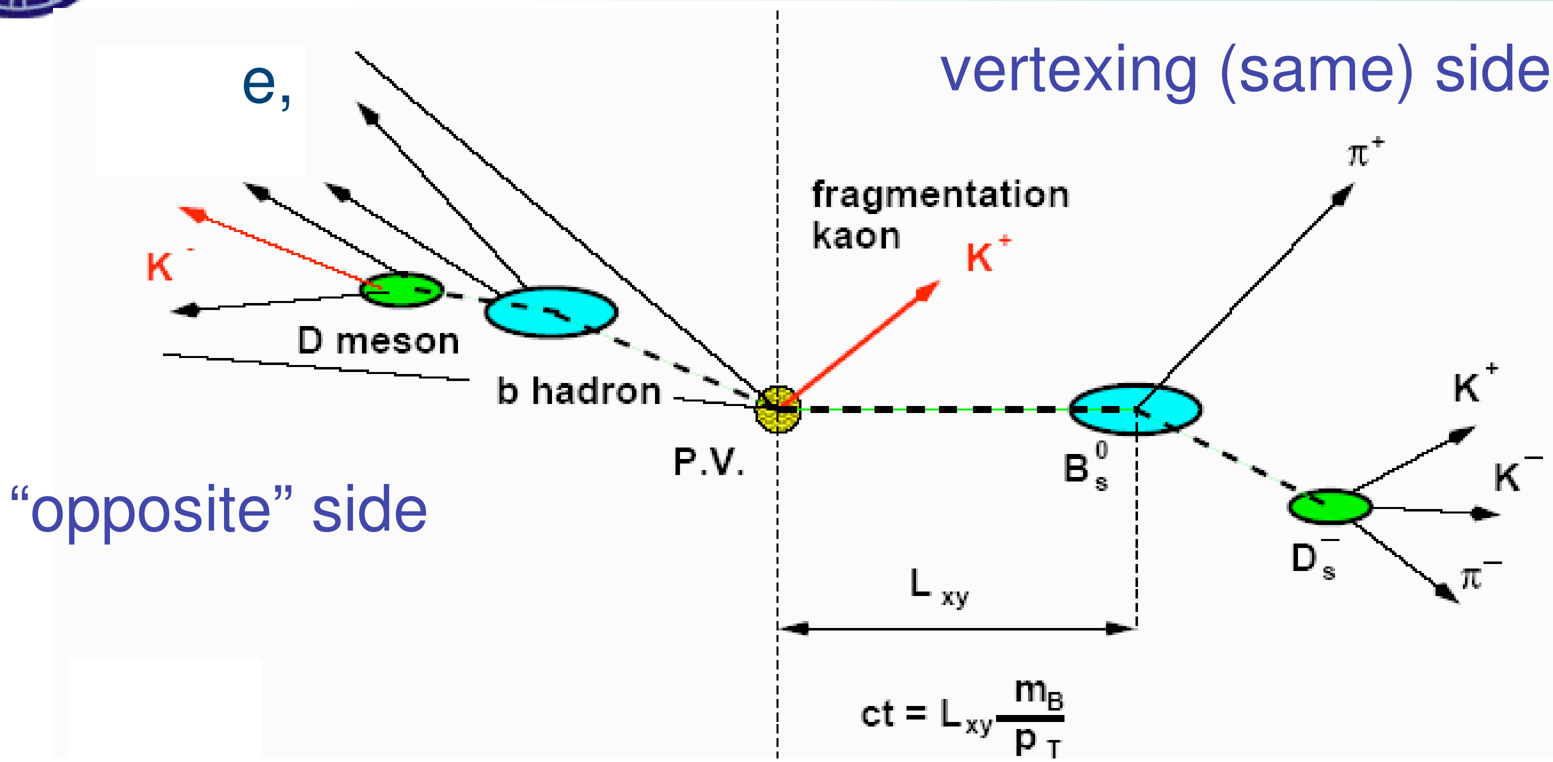




- layer of silicon placed directly on beryllium beam pipe
- radial displacement from beam ~1.5 cm
- additional impact parameter resolution, radiation hardness

Flavor Tagging

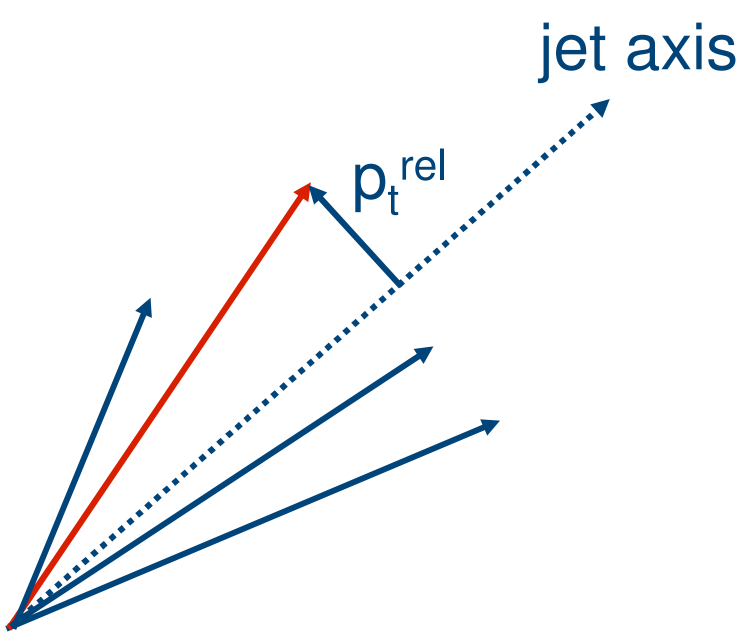
Tagging the B Production Flavor

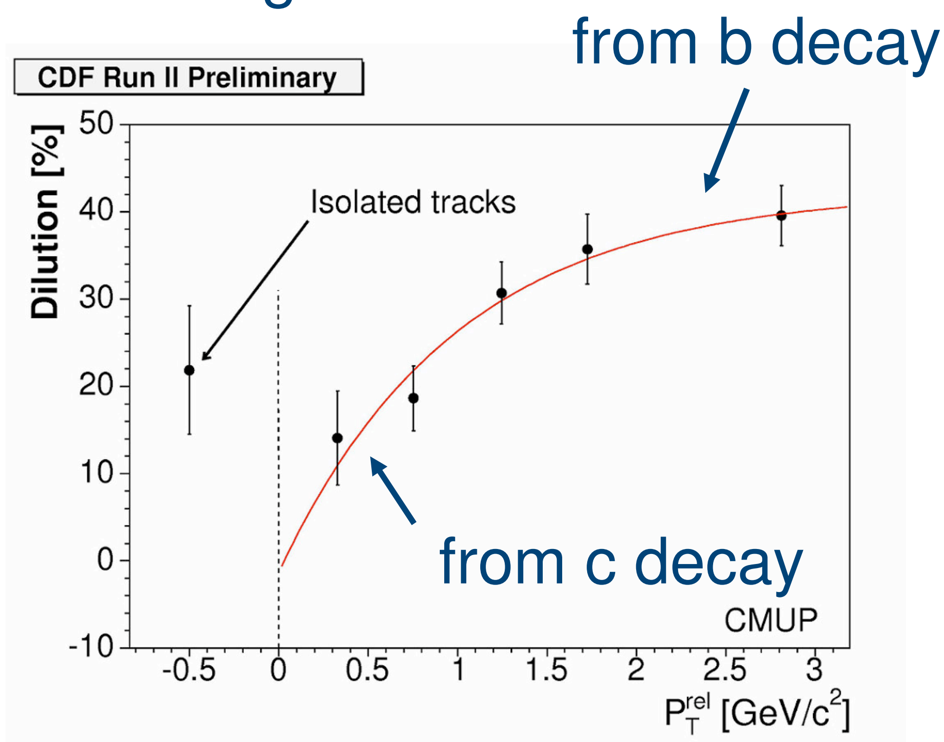


- use a combined same side and opposite side tag!
- use muon, electron tagging, jet charge on opposite side
- jet selection algorithms: vertex, jet probability and highest p_T
- particle ID based kaon tag on same side

Parametrizing Tagger Decisions

- use characteristics of tags themselves to increase their tagging power, example: muon tags



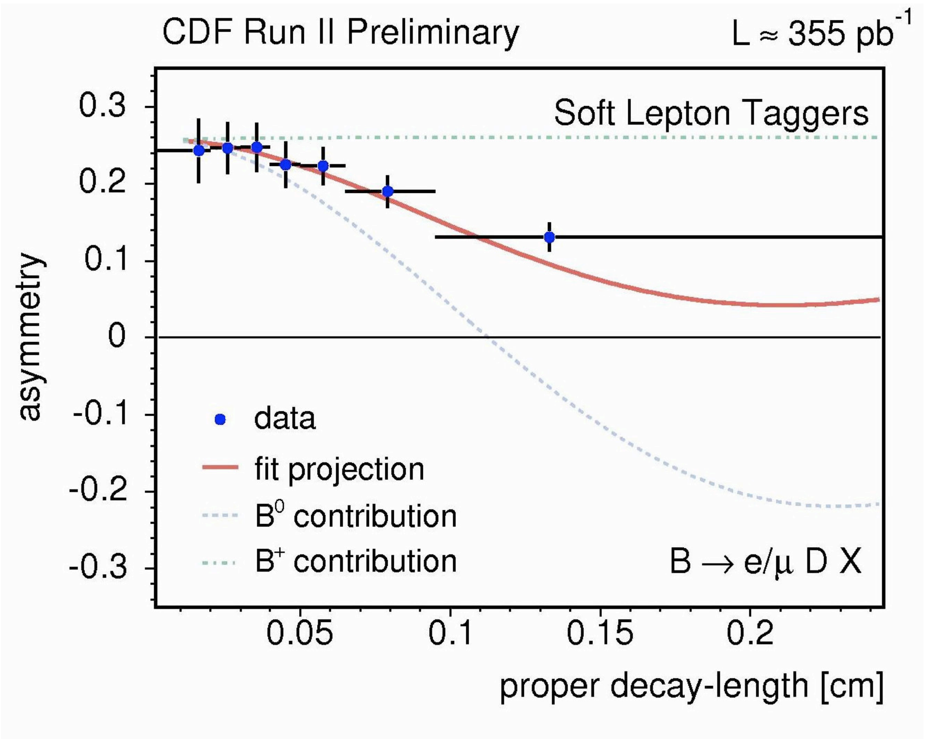


- tune taggers and parametrize event specific dilution
- technique in data works with opposite side tags

Unbinned Likelihood Δm_d Fits

- fit separately in hadronic and semileptonic sample
- per sample, simultaneously measure
  - tagger performance
  - Δm_d
- projection incorporates several classes of tags

semileptonic, ID^-, muon tag



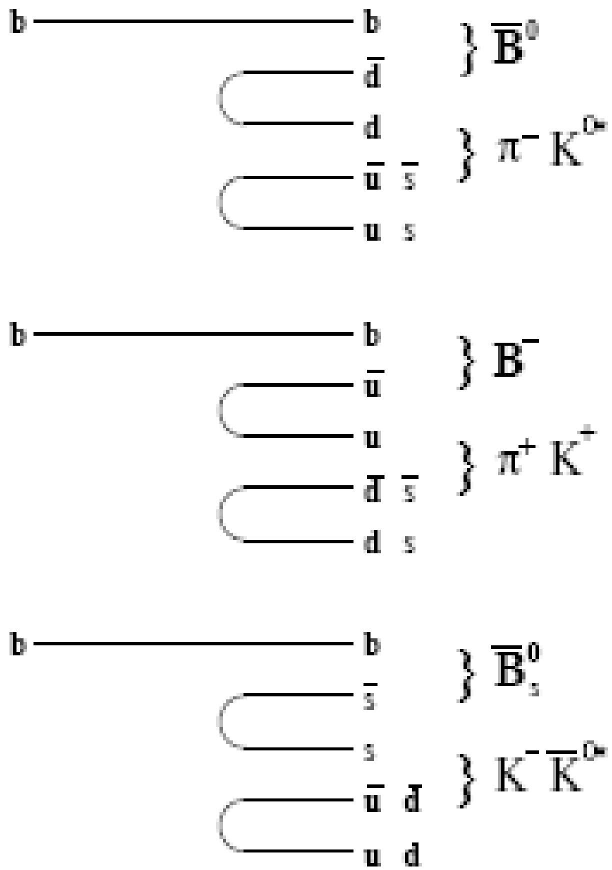
hadronic: $\Delta m_d = 0.536 \pm 0.028$ (stat) ± 0.006 (syst) ps^{-1}

semileptonic: $\Delta m_d = 0.509 \pm 0.010$ (stat) ± 0.016 (syst) ps^{-1}

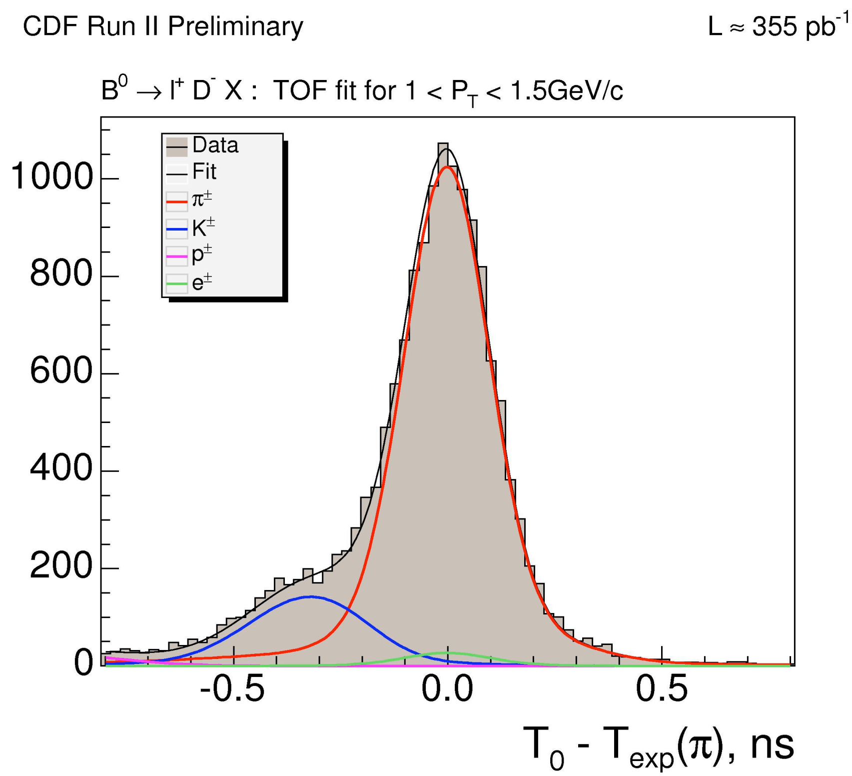
world average: $\Delta m_d = 0.507 \pm 0.005$ ps^{-1}

Same Side Kaon Tags

- exploit b quark fragmentation signatures in event
- B^0/B^+ likely to have a π^-/π nearby
- B_s^0 likely to have a K^+
- use TOF and COT dE/dX info. to separate pions from kaons
- problem: calibration using only B^0 mixing will not work
- tune Monte Carlo simulation to reproduce B^0, B^- distributions, then apply directly to B_s^0

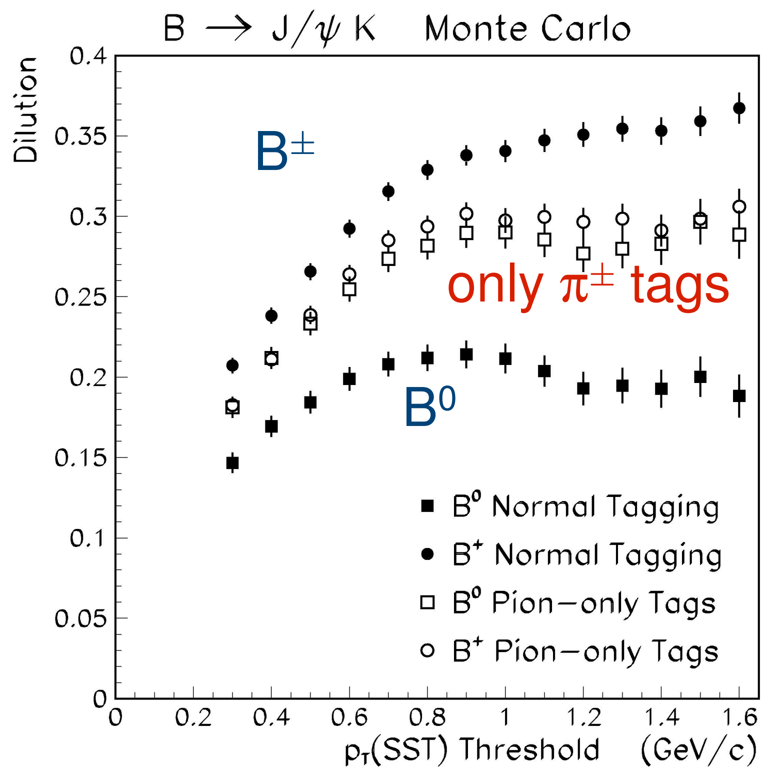


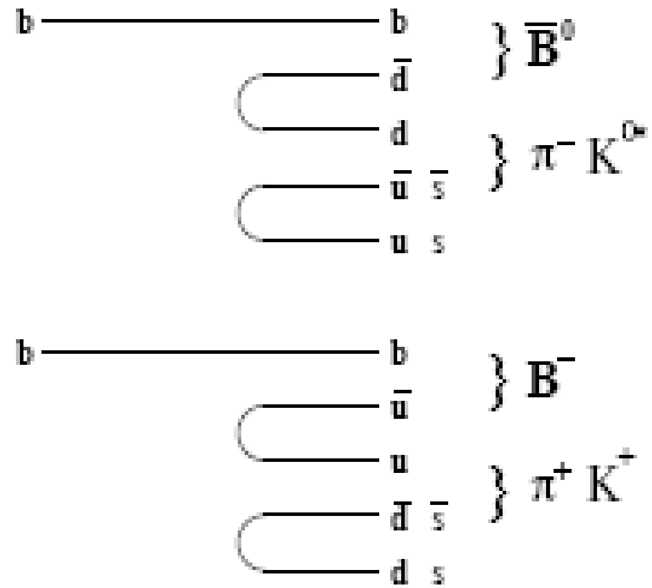
Time Of Flight System



- timing resolution ~100 ps → resolves kaons from pions up to p ~ 1.5 GeV/c
- TOF provides most of the Particle ID power for SSKT

Kaons Matter in Light B's!

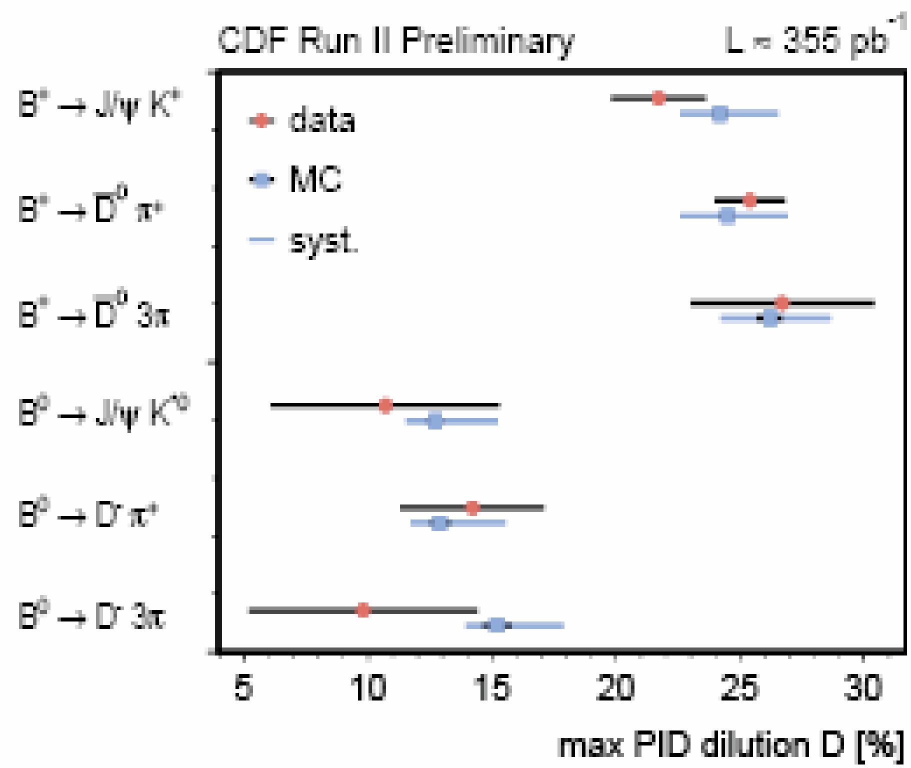




- kaons participate differently in tagging $B^{\pm}$, B^0
- Monte Carlo simulation has to have correct kinematics AND particle content to get the dilution right!

Calibrating SSKT

- Analogous to transfer scale factor in Opposite Side Tags
- Check dilution in light B meson decays



Data/MC agreement is the largest systematic uncertainty → O(14%)

Tagger Performance

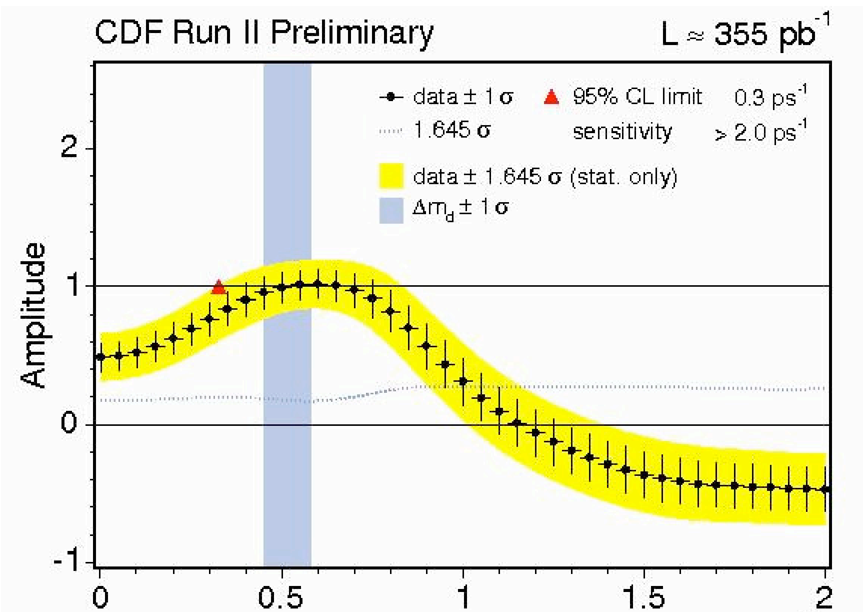
	εD^2 Hadronic (%)	εD^2 Semileptonic (%)
Muon	0.48 ± 0.06 (stat)	0.62 ± 0.03 (stat)
Electron	0.09 ± 0.03 (stat)	0.10 ± 0.01 (stat)
JQ/Vertex	0.30 ± 0.04 (stat)	0.27 ± 0.02 (stat)
JQ/Prob.	0.46 ± 0.05 (stat)	0.34 ± 0.02 (stat)
JQ/High p_T	0.14 ± 0.03 (stat)	0.11 ± 0.01 (stat)
Total OST	1.47 ± 0.10 (stat)	1.44 ± 0.04 (stat)
SSKT	3.42 ± 0.98 (syst)	4.00 ± 1.02 (syst)

- use exclusive combination of tags on opposite side
- same side – opposite side combination assumes independent tagging information

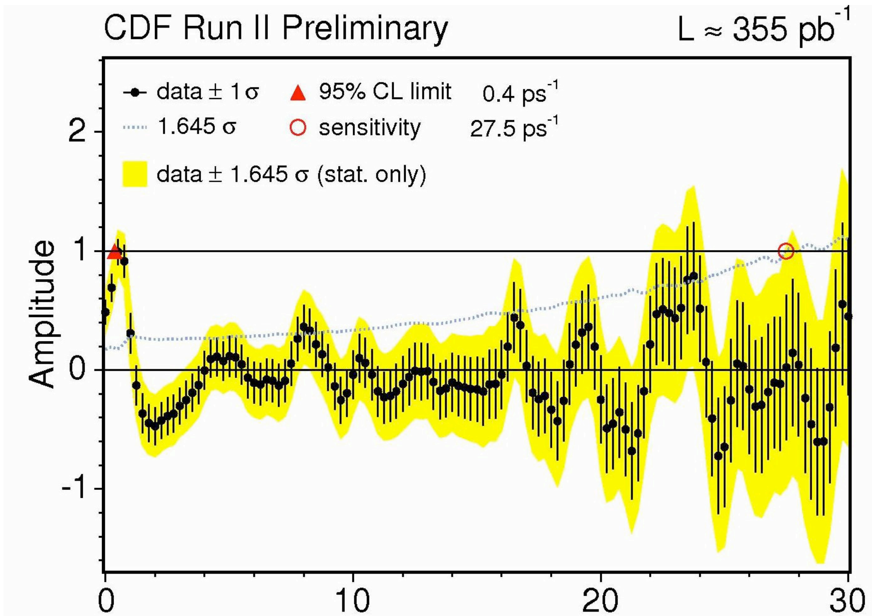
The Procedure

Amplitude Scans

- example: B^0 Mixing signal in hadronic decays
- points: $A \pm \sigma(A)$ from likelihood fit for different Δm
- yellow band: $A \pm 1.645\ \sigma(A)$
- Δm values where $A + 1.645\ \sigma(A) < 1$ are excluded at 95% C.L.
- dashed line: $1.645\ \sigma(A)$ as function of Δm
- measurement sensitivity: $1.645\ \sigma(A) = 1$

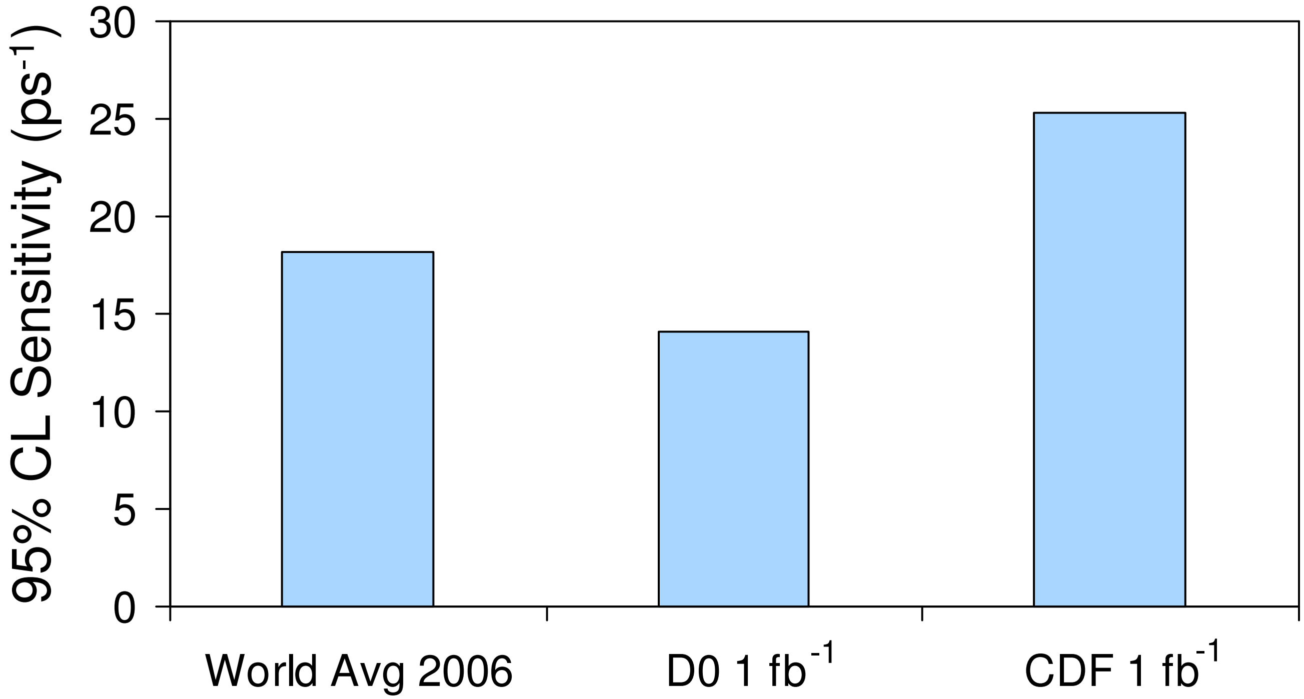


narrow Δm_s range



wide Δm_s range

Measurement Sensitivity



- estimated from data
- unusual situation – one single measurement more sensitive than the world average knowledge!

A Priori Procedure

- decided upon before un-blinding the 1 fb^{-1} of data
- p-value: probability that background fluctuation would produce observed effect
- p-value to be estimated using Δ(ln L) method
- no search window to be used

p-value < 1%?

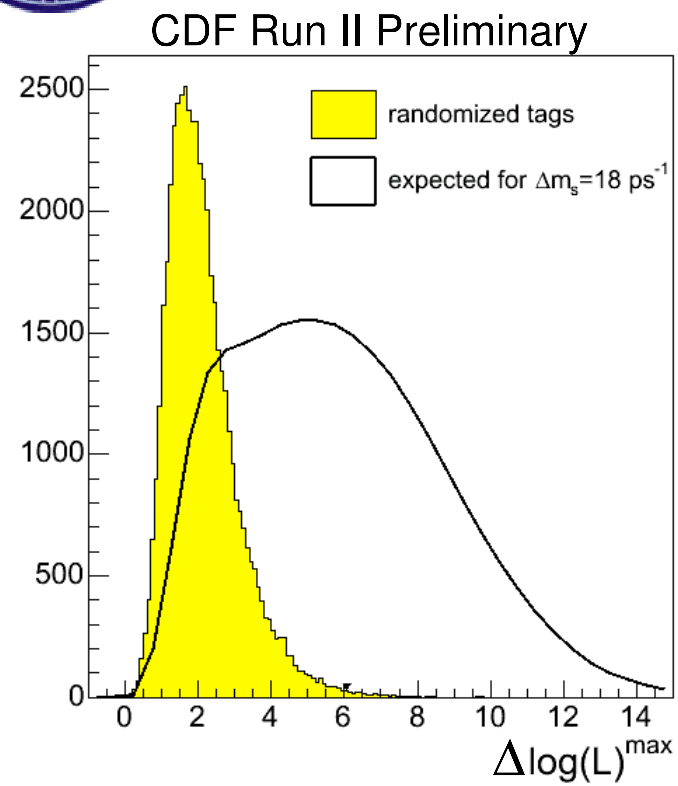
YES

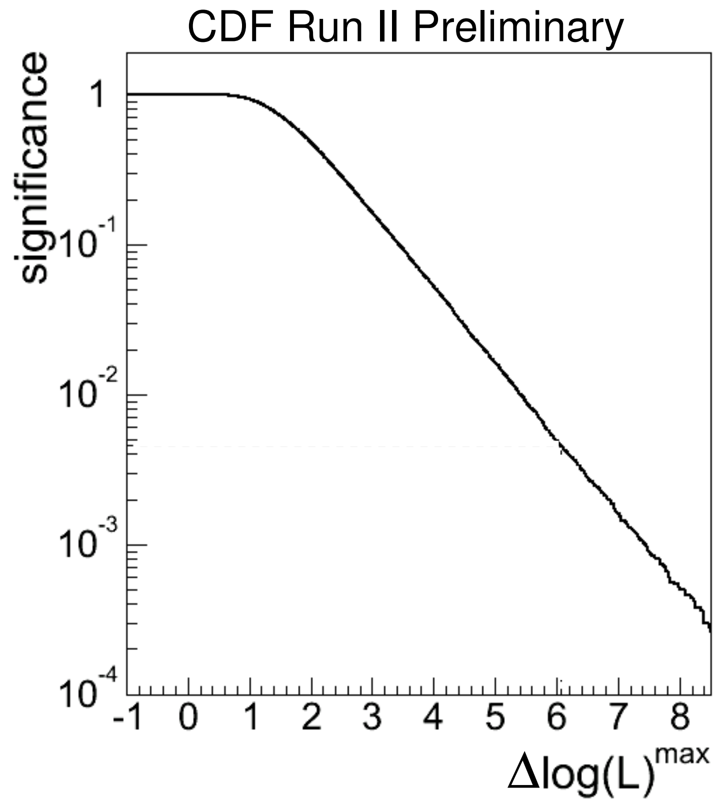
make double-sided confidence interval from Δ log(L), measure Δm_s

NO

set 95% CL limit based on Amplitude Scan

p-value Estimation

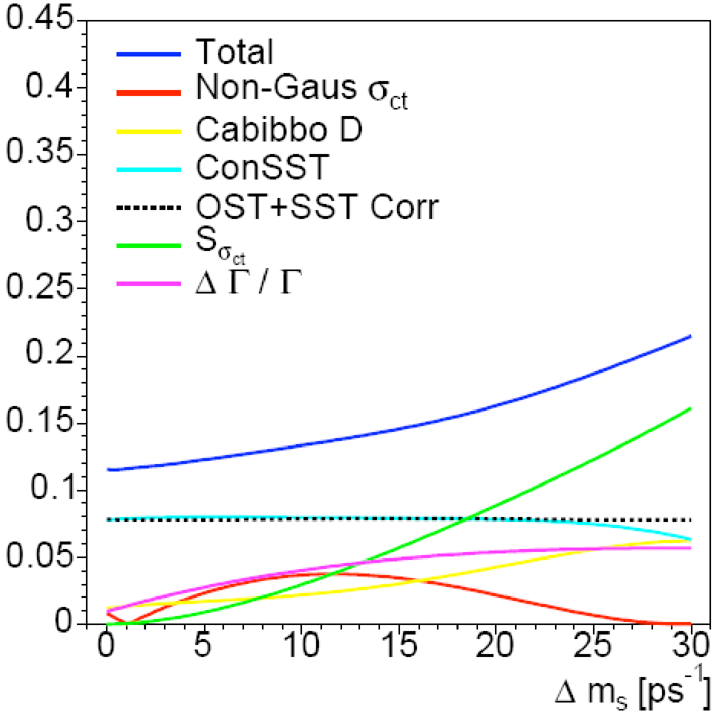




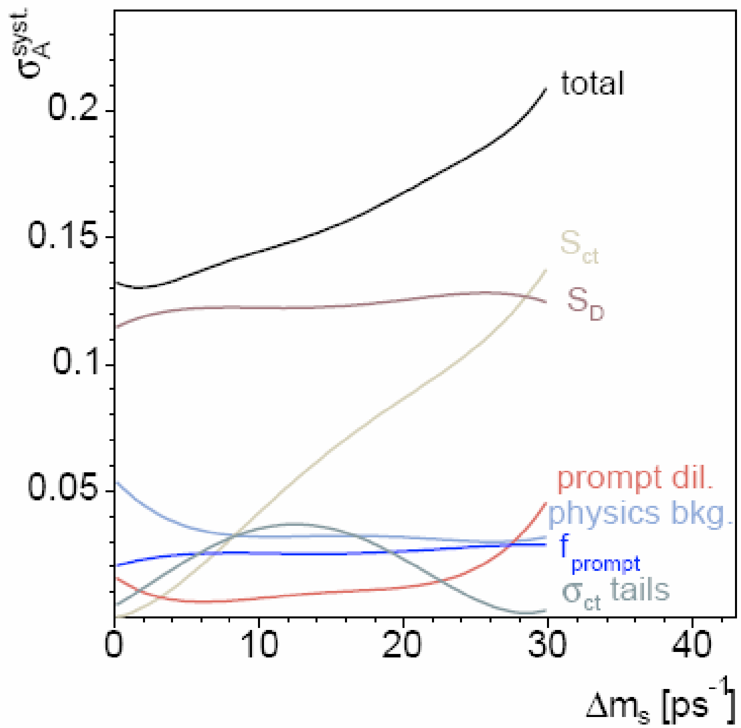
- Δlog(L) = log[L(A=1) / L(A=0)] $\rightarrow$ likelihood “dip” at signal
- more powerful discriminant than A/σ(A)
- probability of random tag fluctuations evaluated on data (with randomized tags) $\rightarrow$ checked that toy Monte Carlo gives same answer

Systematic Uncertainties

Hadronic



Semileptonic



- related to absolute value of amplitude, relevant only when setting limits
  - cancel in A/σ_A, folded in in confidence calculation for observation
  - systematic uncertainties are very small compared to statistical

Systematic Uncertainties on Δm_s

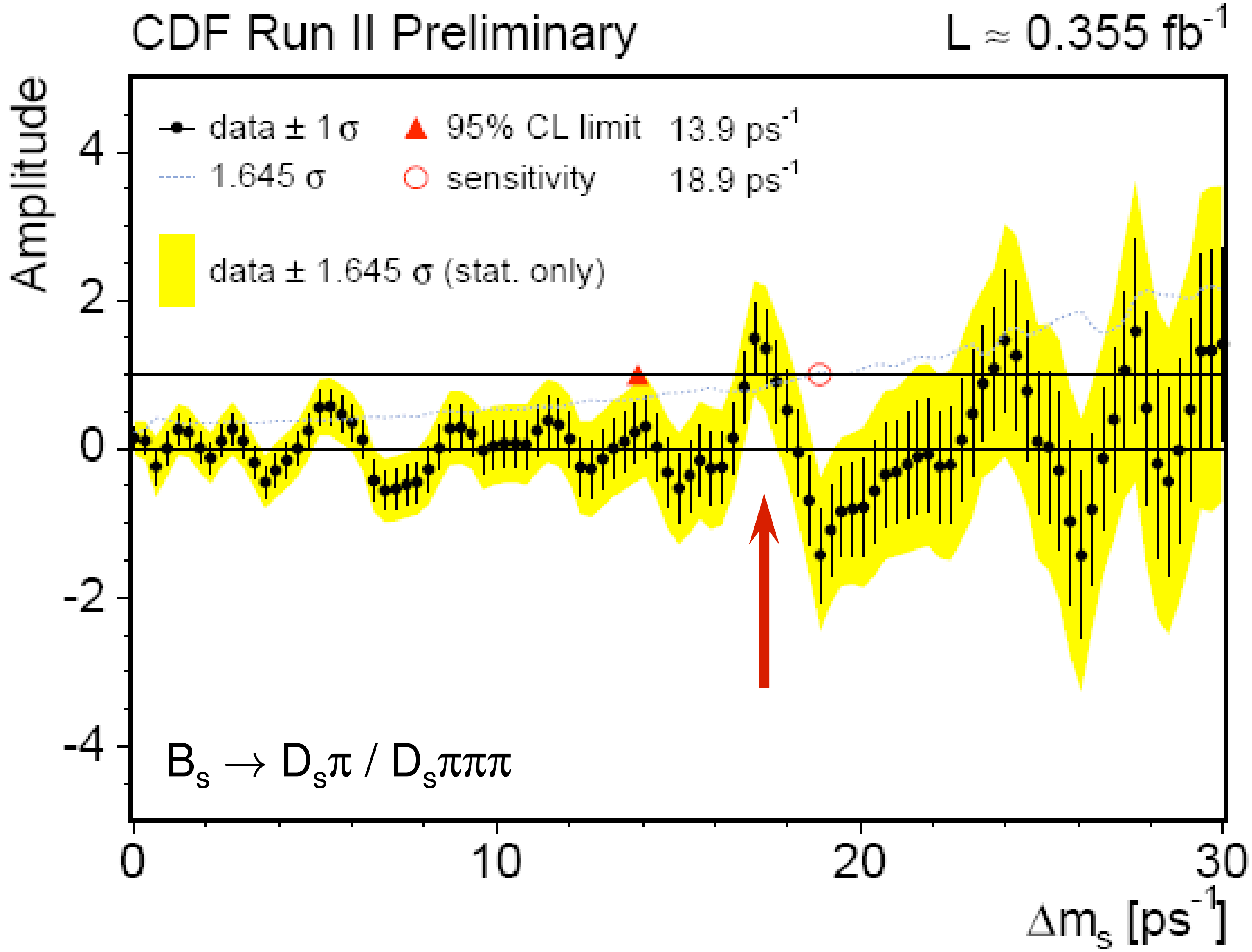
- systematic uncertainties from fit model evaluated on toy Monte Carlo
- have negligible impact
- relevant systematic unc. from lifetime scale

	Syst. Unc
SVX Alignment	$0.04\ ps^{-1}$
Track Fit Bias	$0.05\ ps^{-1}$
PV bias from tagging	$0.02\ ps^{-1}$
All Other Sys	$< 0.01 ps^{-1}$
Total	$0.07\ ps^{-1}$

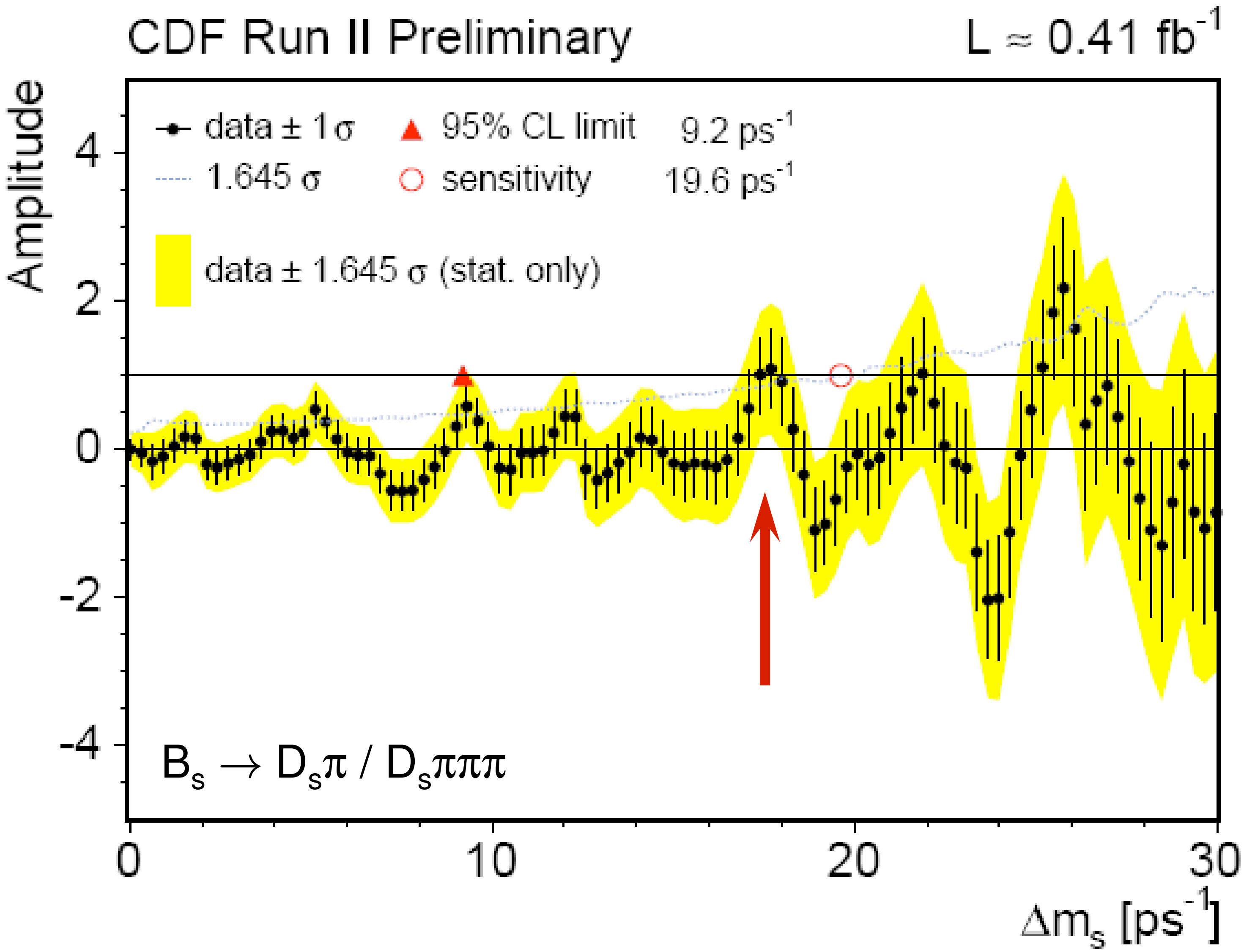
All relevant systematic uncertainties are common between hadronic and semileptonic samples

The Data

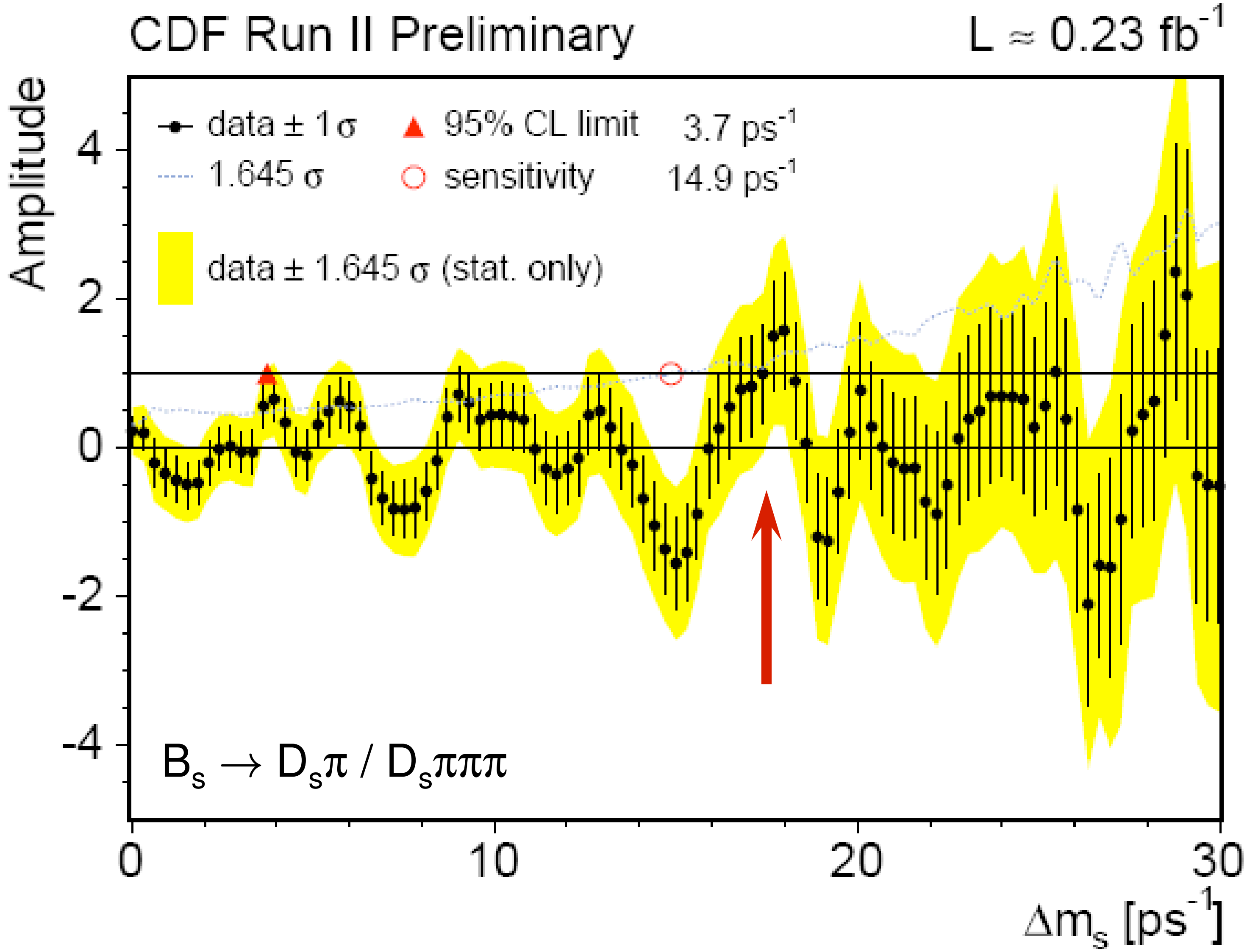
Amplitude Scan: Hadronic Period 1



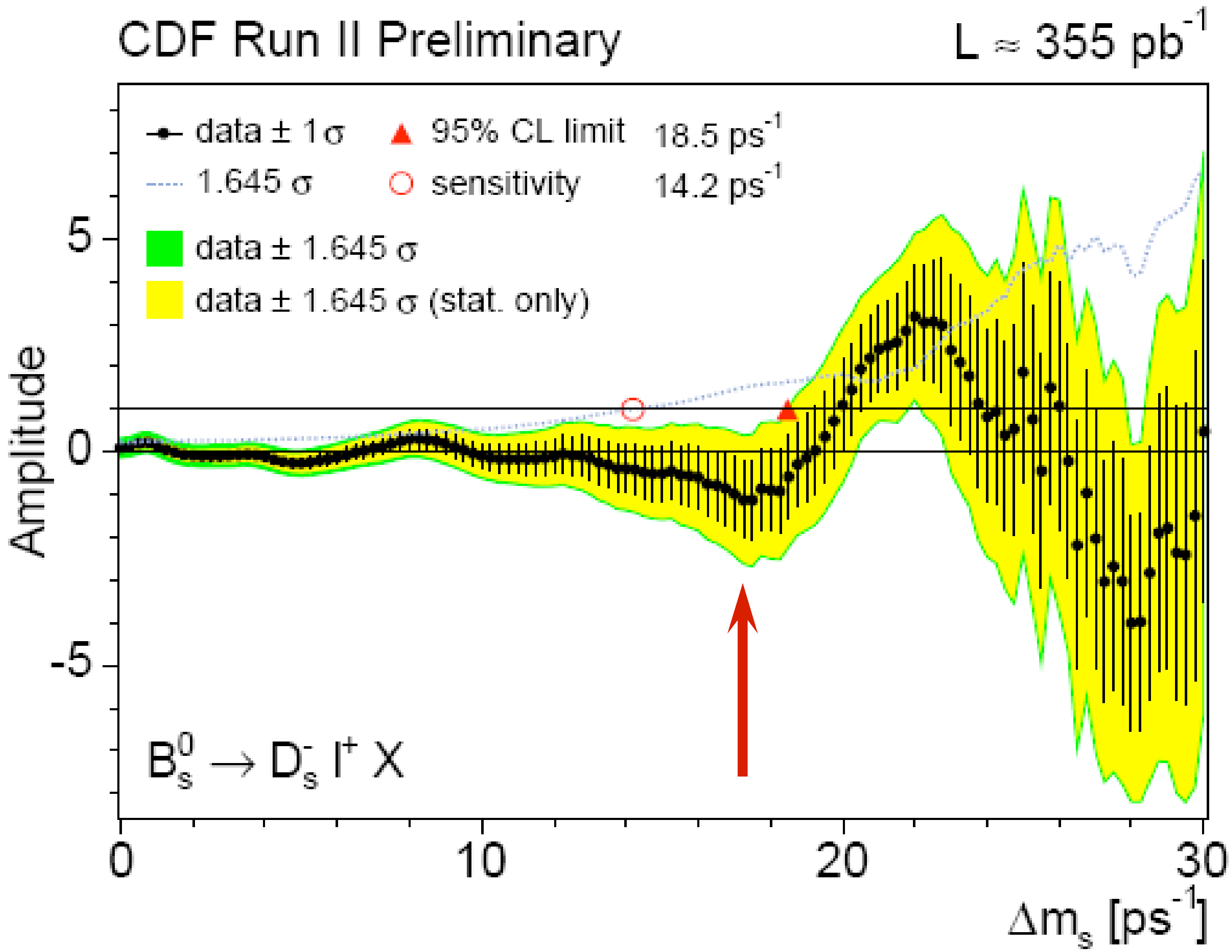
Amplitude Scan: Hadronic Period 2



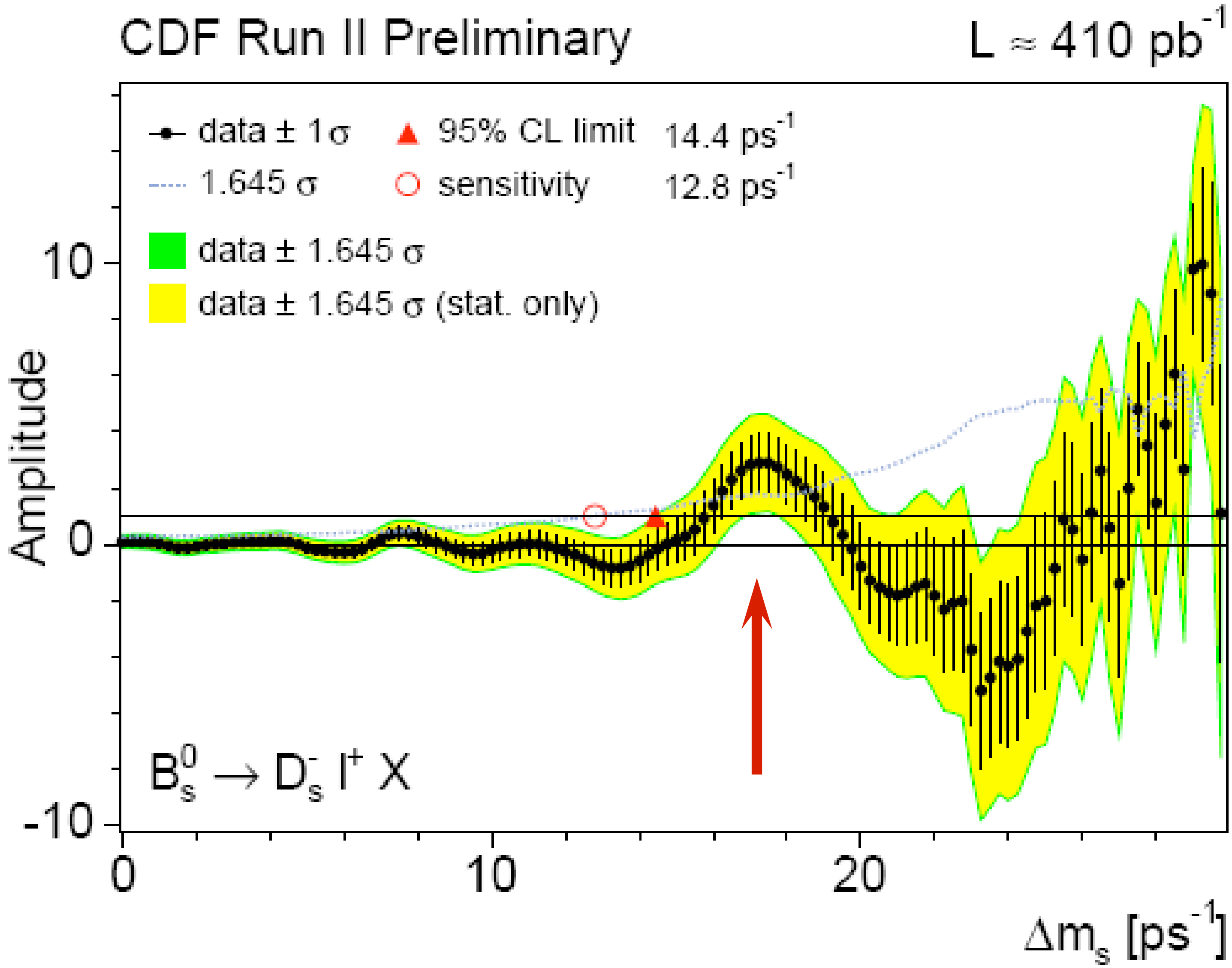
Amplitude Scan: Hadronic Period 3



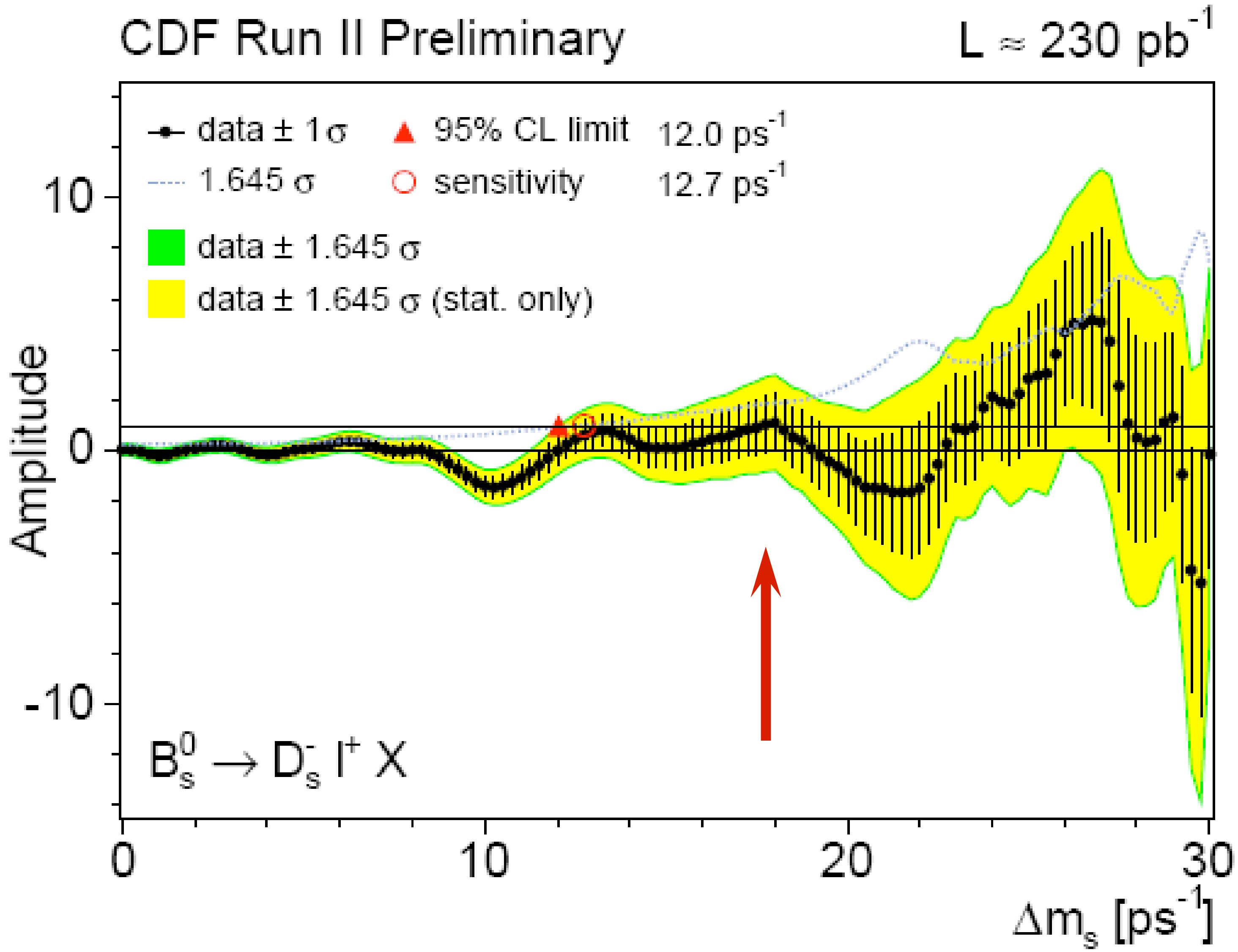
Semileptonic Scan: Period 1



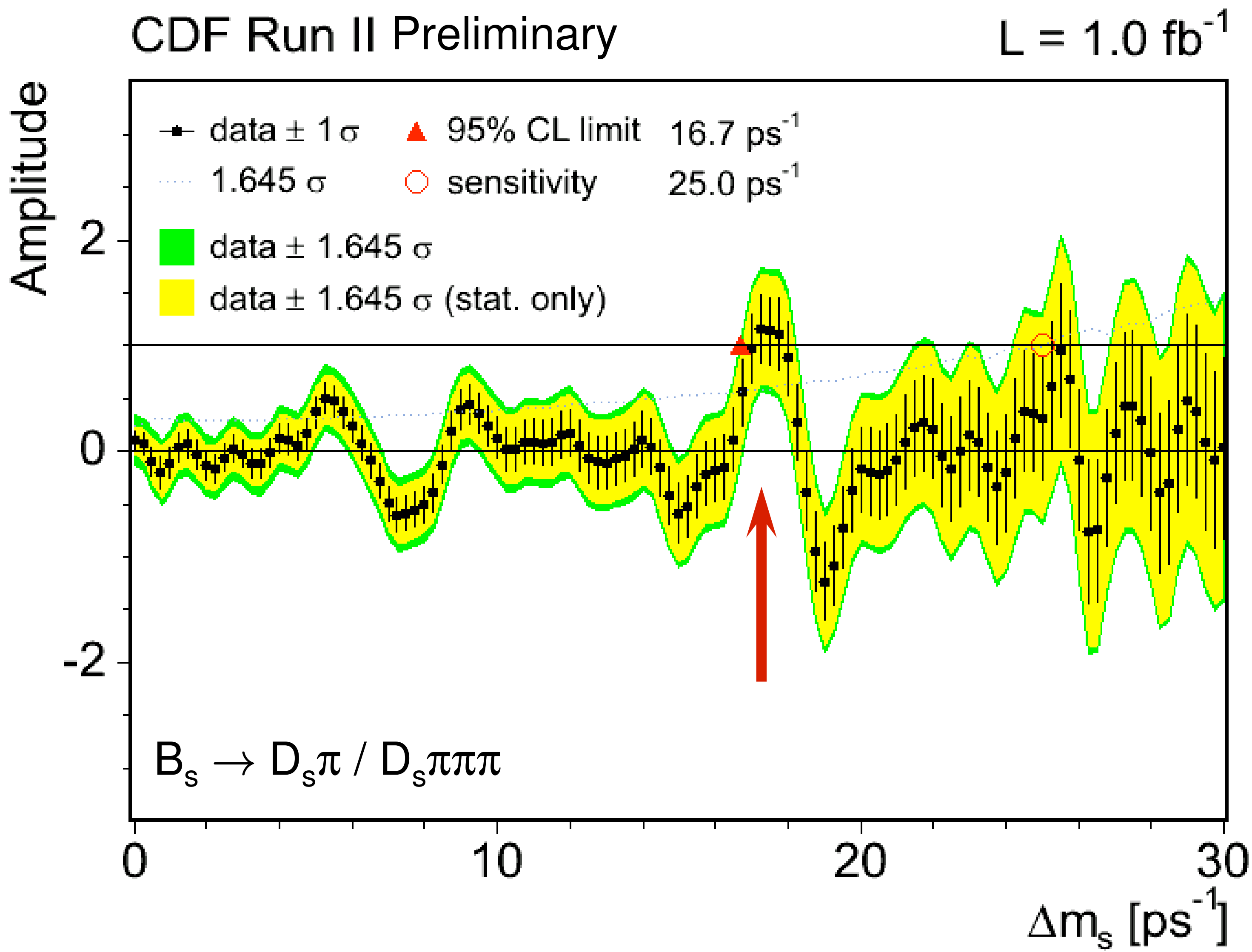
Semileptonic Scan: Period 2



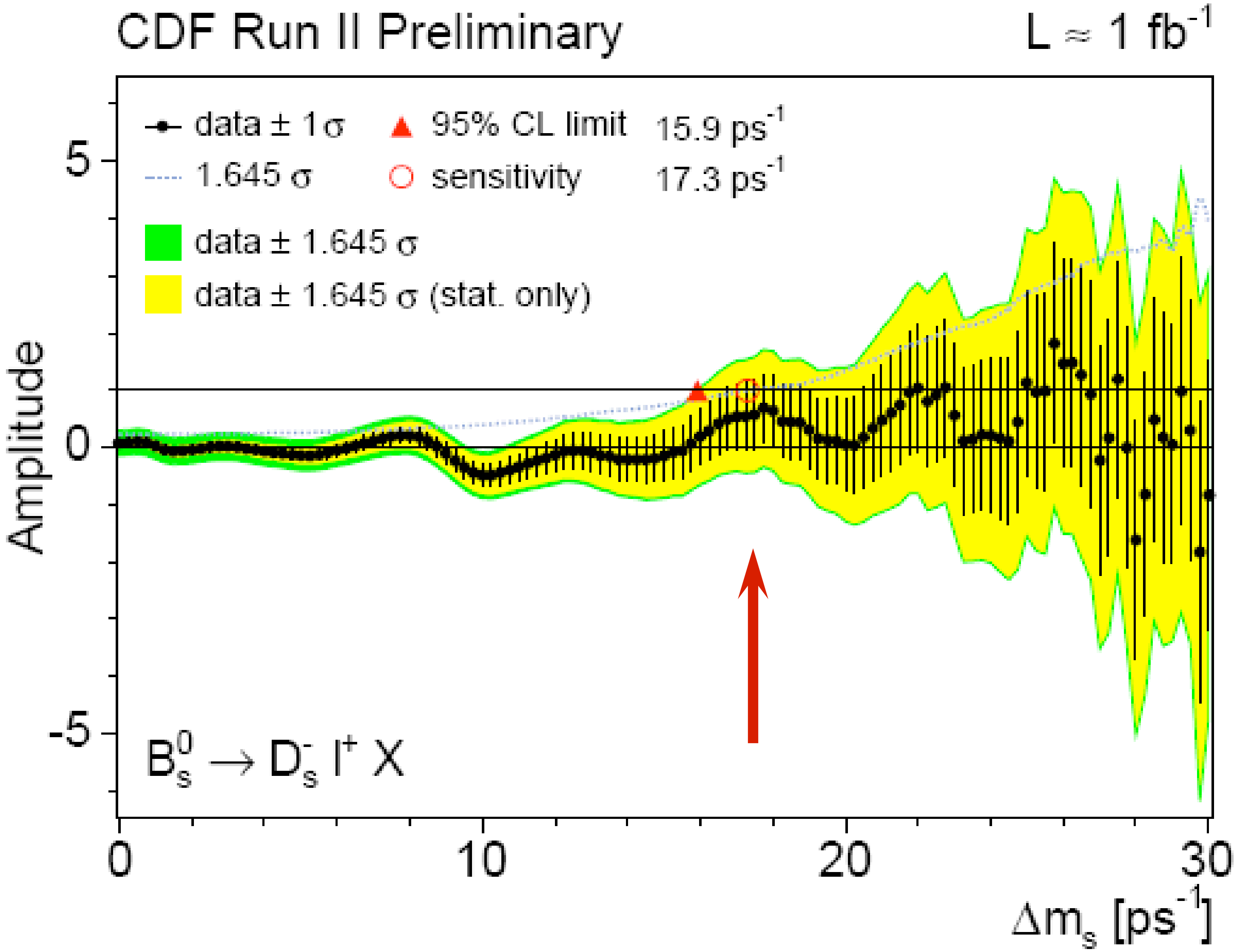
Semileptonic Scan: Period 3



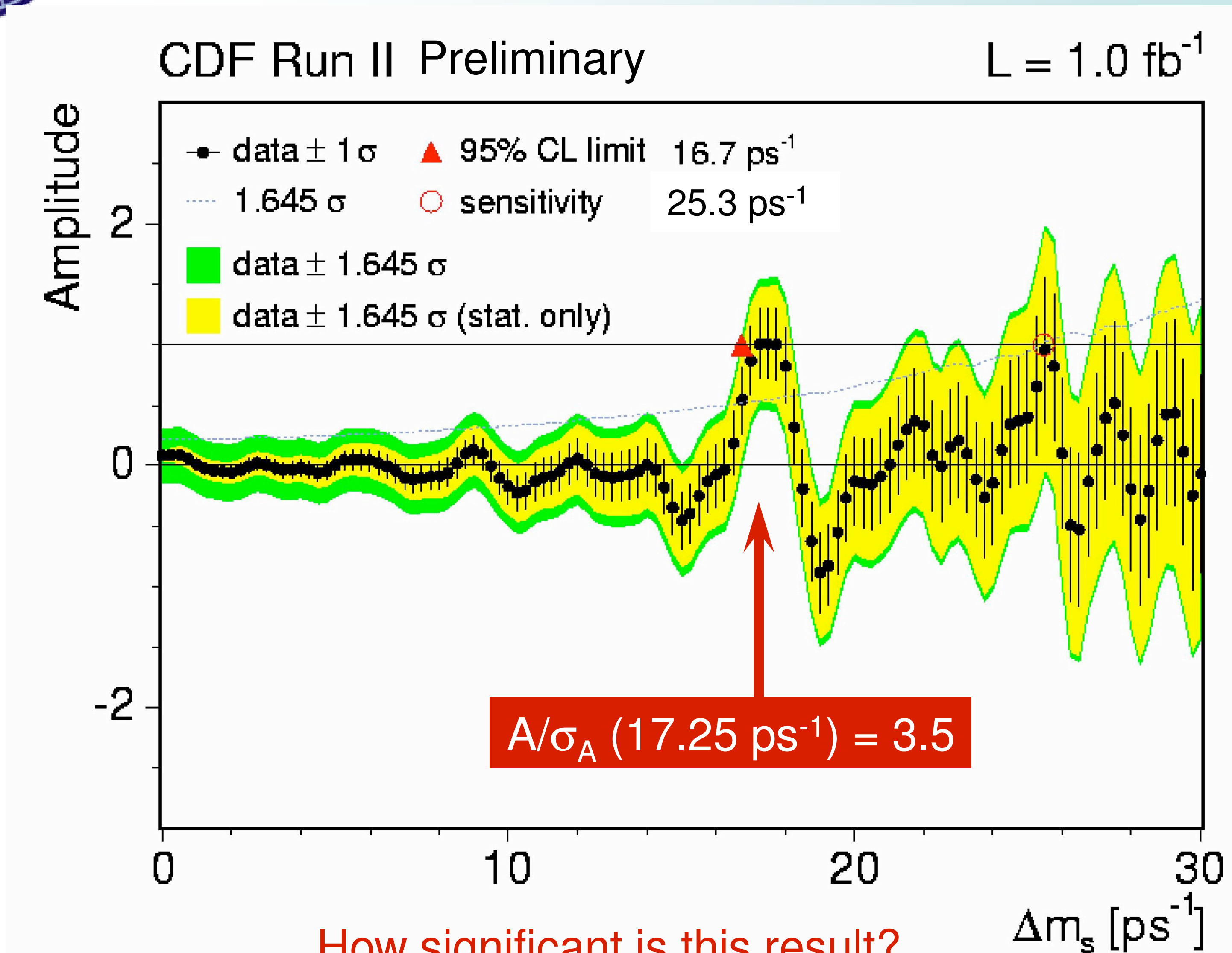
Hadronic Scan: Combined



Semileptonic Scan: Combined

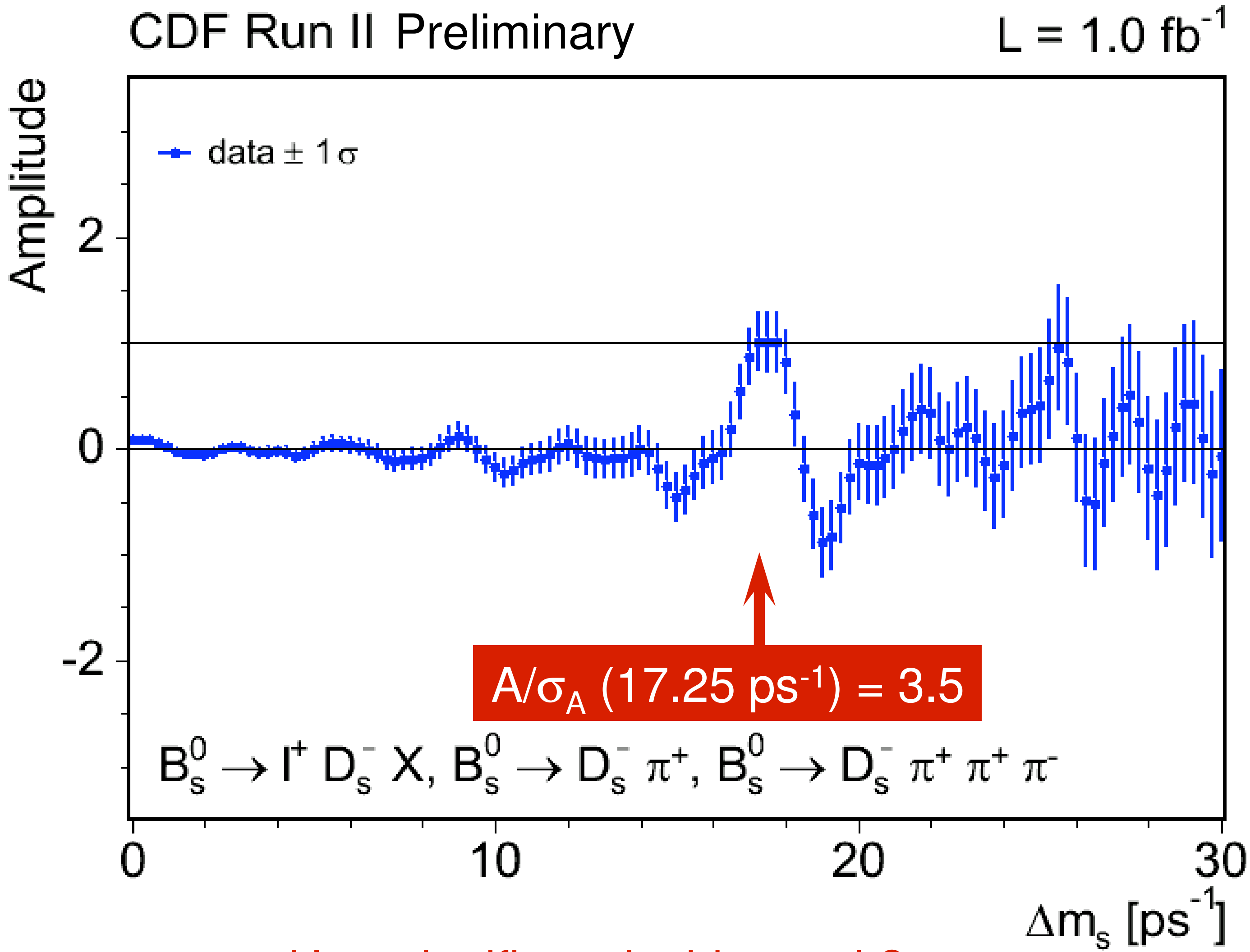


Combined Amplitude Scan



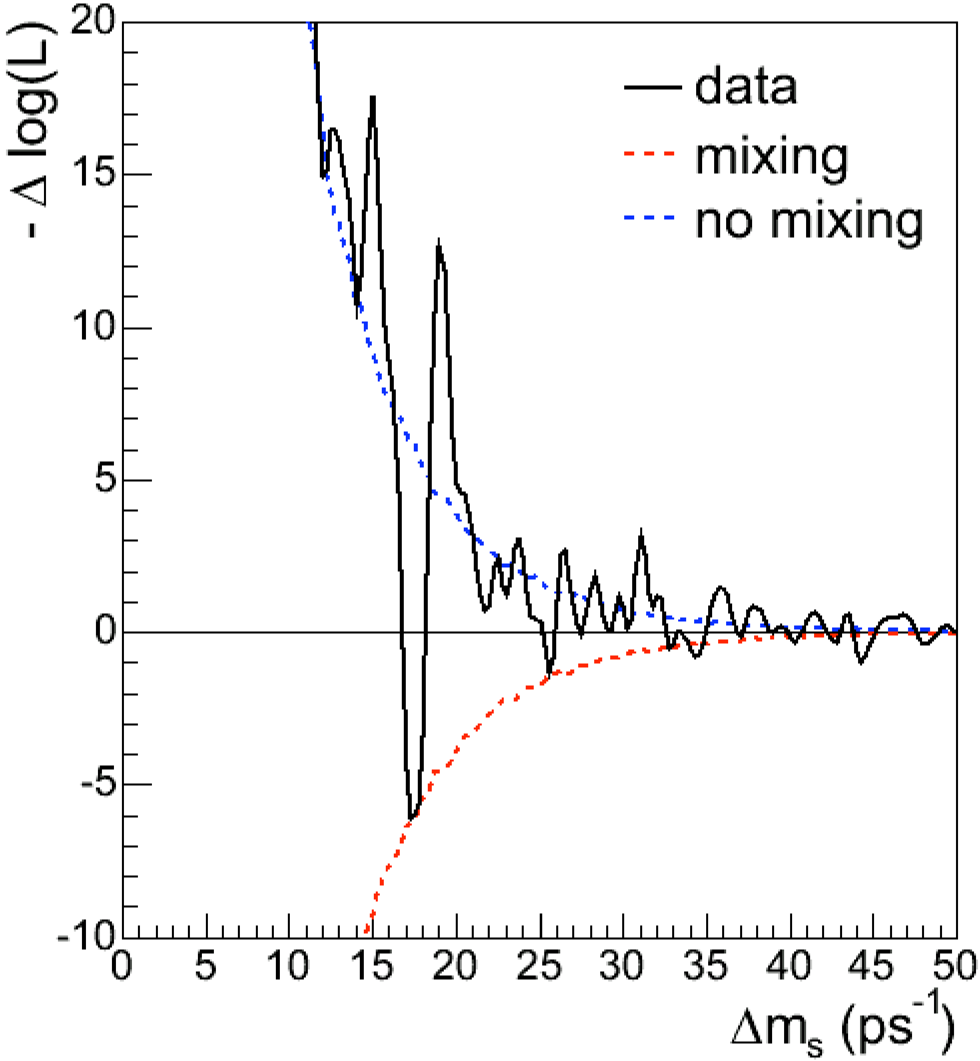
How significant is this result?

Combined Amplitude Scan



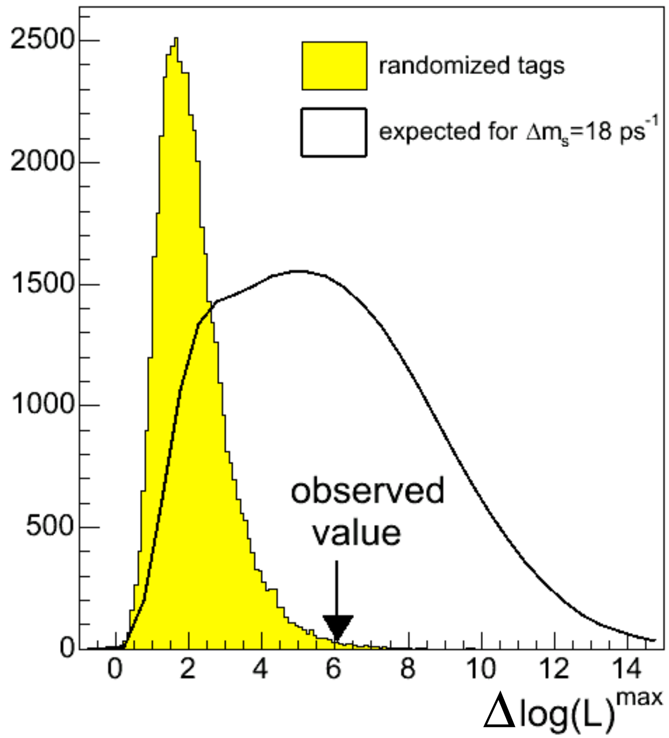
How significant is this result?

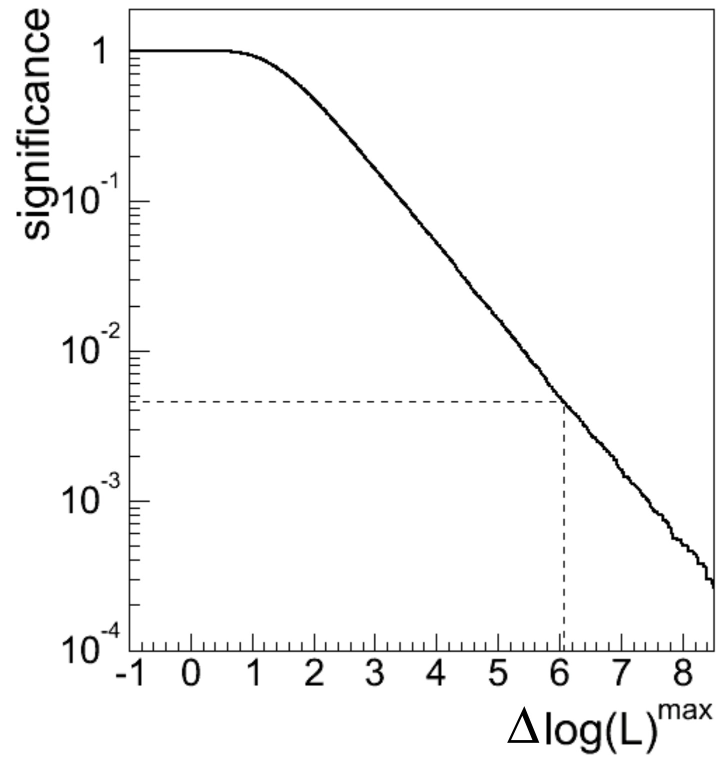
Likelihood Profile



Q: How often can random tags produce a likelihood dip this deep?

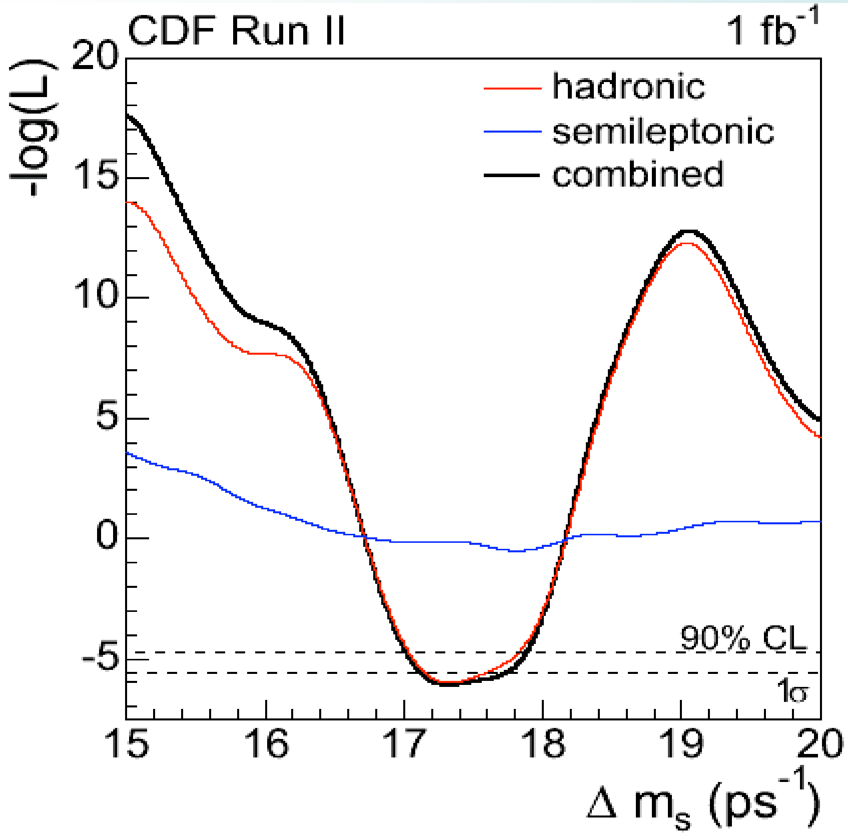
Likelihood Significance





- randomize tags 50 000 times in data, find maximum $\Delta\log(L)$
- in 228 experiments, $\Delta\log(L) \geq 6.06$
- probability of fake from random tags = 0.5% $\rightarrow$ measure Δm_s!

Measurement of Δm_s



$$\Delta m_s = 17.33\ ^{+0.42}_{-0.21}\ \text{(stat)} \pm 0.07\ \text{(syst) ps}^{-1}$$

the measurement is already very precise! (at 2.5% level)

Δm_s in [17.00, 17.91] ps^{-1} at 90% CL

Δm_s in [16.94, 17.97] ps^{-1} at 95% CL

$|V_{td}| / |V_{ts}|$

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

- inputs:
  - → $m(B^0)/m(B_s) = 0.9830$ (PDG 2006)
  - → $\xi = 1.21 ^{+0.047}_{-0.035}$ (M. Okamoto, hep-lat/0510113)
  - → $\Delta m_d = 0.507 \pm 0.005$ (PDG 2006)

$$|V_{td}| / |V_{ts}| = 0.208 ^{+0.008}_{-0.007} \text{ (stat + syst)}$$

- compare to Belle $b \to d\gamma$ (hep-ex/0506079):

$$|V_{td}| / |V_{ts}| = 0.199 ^{+0.026}_{-0.025} \text{ (stat) } ^{+0.018}_{-0.015} \text{ (syst)}$$

Conclusions

- found signature consistent with B_s - B_s oscillations
- probability of fluctuation from random tags is 0.5%

$$\Delta m_s = 17.33\,^{+0.42}_{-0.21}\,(\text{stat}) \pm 0.07\,(\text{syst})\ \text{ps}^{-1}$$

$$|V_{td} / V_{ts}| = 0.208\,^{+0.008}_{-0.007}\,(\text{stat + syst})$$